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"Design and test of a radar"

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" Sólo cabe progresar cuando se piensa en grande,
sólo es posible avanzar cuando se mira lejos."

José Ortega y Gasset

Acknowledge

I wish to acknowledge my tutor, Sergio Llorente, for all his effort and work during this year. I really appreciate his contributions and point of view that guided my work.

I would like to express my deepest thankfulness to my family, who have been my driving force. The three people that, during these 5 years, gave my strength and breath when I could not find it. Once more, thank you.

I would also to thank the eternal fighters, my classmates and friends. The ones that had given and still give the best of them every day of these 5 years. You made every step in the way a little bit easier.

And to you, the one that has handled my stress and my nerves, thanks for your support and your love through this final step of the journey.

Abstract

A Radar (Radio Detection and Ranging) is a device that is capable of detecting targets in its way by the emission and reception of pulses. Electromagnetics, circuit theory, signal theory and some other knowledge are necessary for the description of its behaviour and the design of the radar.

In daily life, radar systems with different simplicity levels are used for several number of applications such as weather prediction, speed measurements, aircraft landing, security alarms, maritime navigation and uncountable more uses.

However, this study will focus in the design of a simple device that detects targets in short-medium distance. Radar system will be divided in different components and blocks that will be designed and tested in order to obtain their best performance for the system.

The system designed is expected to generate pulses that will reach the targets in the surrounding. The reflection of the wave on these targets will generate and echo that will be absorb by the antenna.

The signal received will provide information about the target such as its range, its speed, its angle or its shape.

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Chapter 1

Introduction

Nowadays, radars are more often used for detection of obstacles or any other object in our sight. Size, speed, angle or position of any target can be determined thanks to the measurements computed by the radar system.

Due to the increase of the use of this kind of devices, this study intends to analyse and test a small radar in a common environment.

The purpose of this chapter is to establish the objectives of this project and the problems expected to find in order to achieve them. However, final solutions and implementations made in order to solve these problems will be explained at the end of this study.

The following chapters will give a brief look to the history, main features and blocks of radar, along with the characteristics and test of every component in the system.

Once the whole radar system is designed, its test permits the analysis of every important signal and wave in the system and the explanation its characteristics and relationship with the components and technology used.

1. Objectives.

The objective of this thesis is to **cover the basic principles of radar system and its design.** The completion of this study means to increase our knowledge regarding RF, analogs, electromagnetics, signal processing and some other principles of radar.

This project will be based on the MIT Course *"Build a Small Radar System Capable of Sensing Range, Doppler, and Synthetic Aperture Radar Imaging"* that shows all important aspects regarding the design, test and construction of a Synthetic Aperture Radar (SAR).

For the design of the radar, it will be necessary some knowledge regarding all characteristics and working principles of each component in the system. This matter will make us dig deeper into understanding every aspect of radar design and all technologies used.

2. Fundamentals of radar system.

The main goal of this research will be to design **a radar system that will be able to determine shape, distance and speed of targets in the detection range**, also **avoiding ghosts** created by disturbances, objects or noise in our spectrum.

For this purpose, a pulse will be generated with **enough power to reach a target**. The echo reflected from the target will be analysed at the receiver block. Its frequency and power will determine the size, speed and distance of the reached target.

The transmission aims **not to disturb the rest of the frequencies of the spectrum** which are not for free use. The range of frequencies assigned for free use are determined by Spanish and international legislation [3] [4].

Regarding the design and construction, the **size of the radar should be minimised**, so the system would be as compact as possible and it will use the minimum resources. The **price of the designed system** ought to be also **minimized** due to the limitations of the project budget. The radar will be designed in order to use the available resources, devices and components in laboratories. This issue could limit the quality and accuracy of the system.

3. Problems we expect to find and solve.

The problems faced during the design and test of this system could be easily found by analysing the project step by step. Two different kind of problems will be face during the development of this project, those will be technical and external problems.

As external problems, this project is facing legislation issues, environmental issues and issues related with budget of the project and available technology at the university.
According to the legislation, there is a free band of the spectrum that could be used for the radiation of emitted wave. The width of this band is established by regulatory bodies and laws that will be describe at the end of this document.[4]
The radiated wave and devices used are not dangerous for environment or human being. The radiation at these frequencies is like the one emitted from a phone or a router in wifi emission.
Regarding the budget of the project, there are certain components or technologies which are not affordable due to the limitations established by university resources or the budget assigned to this project. The project needs to overcome these problems and find suitable technologies for the system that would be part of university or our own resources.

On the other side, technical problems will depend mostly on the devices used, the radiation , the interferences, losses and nonlinear behaviours and also the lack of power in order to detect targets.
The radar designed needs to minimize those parameters and increase the power in order to be able to overcome the threshold of detection, or minimum power needed to identify a target.. Those losses, attenuation and nonlinear behaviours can come from amplifiers, filters or oscillators that are used in radar system.

Regarding the transmitted signal, the need of power in the transmitted band of spectrum needs to be joined with the limitations imposed by non ideal components used for this construction.
The received signal needs to be analyse without attenuating it or changing it but adequating this signal to the spectrum the spectrum analyser or the computer used.
There are some problems which will need to be faced in order to achieve this goals . All of these problems and the solutions implemented during the design will be listed and explained at the end of this text.

4. Tools and programs used

All systems used for the design of the radar needed to be tested. Find here all different tools and programs used for this purpose.

- AWR Microwave Office : It had been used for simulation of radio frequency systems and circuits. This program is briefly used in some course during bachelor years.

- CST Studio suite : It could had been used to simulate and design the antennas that are going to be used in this system. However, the usability of the student version of the programme is quite limited.

- ANSYS HFSS (High Frequency Structure Simulator) : This program had been used instead of CST for design and simulation of antennas. The usability of this program with higher frequencies is better.

- Autocad : It had been used for protoshield design of each element in the system. There was no previous experience with it so the completion of this project included also getting familiar with this kind of program.

Chapter 2

Radar system

This chapter will give a brief explanation regarding the state of art and history of radar technology and dig deeper into the main principles, features and blocks of radar.

The working principle, components and design of the radar constructed in MIT course "*Build a small radar capable of sensing range, doppler and synthetic aperture radar imaging.*" will be also explained and compared with the ones that are going to be implemented in the radar system object of this study.

1. Radar

A radar (*Radio Detection and Ranging*) is a system capable of detecting targets and establishing their range, angle, size, features or velocity.
In this device, the transmitter sends out a signal radiated by a transmitting antenna. The receiver detects the echo of the wave reflected from target and absorb it. Using this signal, it will be possible to determine the characteristics of the target reached.

1.1. Radar history and current situation.

The idea of radar comes from the theory and experiments about electromagnetic radiation conducted by Henry Hertz in the 1880s.
He tried to prove, using Maxwell's equations, that electromagnetic waves, like light waves, can be reflected from a metallic surface but refracted by a dielectric medium.

In the 1930s Christian Hülsmeyer used Hertz studies to develop a simple device capable of detecting obstacles. At that time, there was simple no interest in this kind of devices, but when World War II started in 1939 these devices became important for allies and nazi's armies.

At this time, all radars where operating in VHF band with a frequency close to 200 Mhz, except for German devices that operated at 375 and 560 Mhz. These frequencies were more sensitive to noise, rain or some other kind of distortion, so the accuracy of this kind of devices was not optimum.
After the war, higher frequencies were used in radar transmission. The accuracy of the detection and vulnerability to noise were increased, so the quality of the radar device increased along with these characteristics.
The development and design of tracking devices like radar grew especially with the invention of the magnetron in 1939 that allowed manufacturers to reduce the size of this device.

This magnetron became the basis of the studies in MIT in Massachusetts, authors of the course "Build a Small Radar System Capable of Sensing Range, Doppler, and Synthetic Aperture Radar Imaging" which is the basis of the radar design in this study.

After the war, the uses of this kind of system were more diverse and nowadays, they are used in many fields.
The diversification in use allowed manufacturers to create different types of radar depending on its use and application. Many techniques were mainly used in the post war radar and they have been modified and matured to accomplish the goals for this system.

Nowadays, radar systems have a lot of applications such as civilian application, military application and scientific applications.
To show some examples, as civilian applications we could mention airport surveillance, weather radar, speed measurements; as military applications, some examples could be missile guidance, detection and tracking of missiles, aircraft and spacecraft; as scientific applications, we could mention astronomy or mapping and imaging. For further applications or information about radar uses, give a look to [1 ; Ch. 14.3]
Small devices that performs the same operation as radar are being constructed for simpler applications in daily life. Detection of presence, speed measurement or altimetry are some radar uses for daily operations and applications.

1.2. Radar system

1.2.1. General scheme of radar

The figure 2.1. shows all functional components of a radar system. The following paragraphs are going to be a brief explanation of its behaviour and the task of each component included in the scheme.

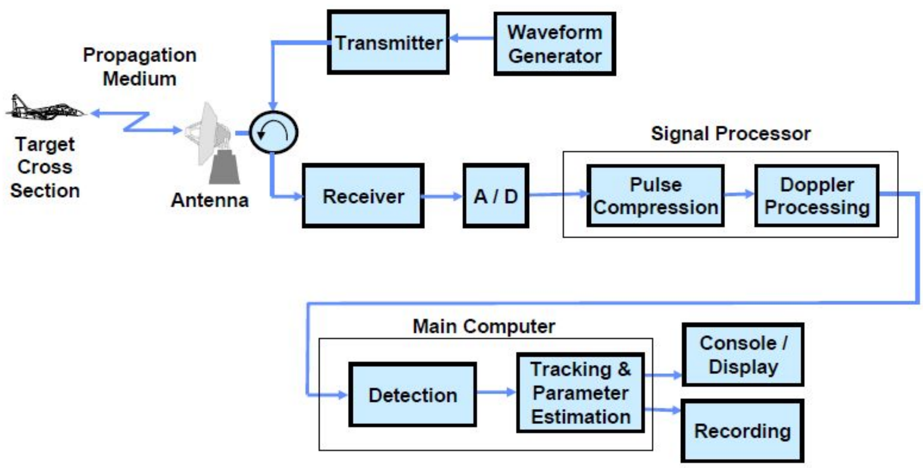


Figure 2.1. Block scheme of radar from MIT Open Course Build a small radar[3]

The waveform generator produces a signal that is sent to the transmitter. The transmitter is in charge of generating pulses with enough power and duration to be transmitted to the antenna and radiated by it.
Once the radiated wave reaches a target, an echo is generated from the reflection of the signal with the object. The echo signal is absorbed by the antenna and sent to the receiver. After some transformation regarding the pulse duration or the frequency of the modulated signal, this information is sent to the main computer.
The analysis of the received signal in the computer can determine the speed , the size, the range and the angle of the reached target.

1.2.2. Main principles

To characterize the radar, it is important to explain the behaviour of this device and what it is needed to consider when constructing, developing or using one. For further information about these principles, check *MIT courses* [5][6] or chapter 4 of *Microwave engineering* [1; Ch. 4]

1.2.2.1. Target crossed section

It is the surface of the target that could be detect. It is defined as the scattered power in a given direction and it depends on the incident and reflected angles and on the polarization of incident and reflected wave.

According to MIT [5] it can be determined by using full scale measurements, scale model measurements or scale model measurements. For further information, check the slides from their curse. [5]

1.2.2.2. Propagation effects

Propagations effects are characteristics of the surrounding media that can attenuate, reflect or bent radar beams and increment their effect with higher frequencies.
Some propagation effects that would need to be consider are atmospheric attenuation, reflection off of Earth's surface, over-the-horizon diffraction, atmospheric refraction in the environment surrounding.
For further information or consultation, check MIT course about basics in radar design [5].

1.2.2.3. Doppler effect

The doppler effect shows that the changes in the frequency of a received echo after detection of a target allows us to determine the distance, shape and speed of the target.
Doppler's frequency is defined as the difference in phase of the quadrature and in phase components of the received signal. Its relation with the velocity of the target could be seen in Formula 2.1.

$$f_d = \frac{2V}{\lambda} \qquad (2.1)$$

being fd the difference in frequency between the emitted signal and received one. The velocity of the target V and the wavelength of the wave received.
Considering V as the velocity, it is possible to determine the distance of the target knowing pulse repetition time (PRT).

1.2.2.4. Resolution of radar.

The resolution of the radar is its capacity to distinguish between two targets that are very close in space. It is determined by the bandwidth of the emitted pulse.

$$Sr \geq \frac{C_0}{2\,BW} \tag{2.2}$$

where BW : bandwidth of emitted pulse; Co : speed of light

1.2.2.5. Threshold of detection

The threshold of detection is the minimum amount of power received in order to consider the blank shown in the power spectrum, a target.
This threshold level determines whether the blank shown is a detected target or a ghost. It should be settle to an appropriate value so there will not be any missed targets in the range of detection.

1.2.2.6. Radar equation

The radar equation determines the level of power received for the detection of a certain target at a known distance in the surrounding space.
The power received from the target depends on the target`s characteristics but also on the features of the system designed such as its transmitted power, the gain of its antennas or the wavelength of the radiated wave.

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}. \tag{2.3}$$

being Pt = peak transmitted power ; G = Gain of the antenna ;
R = distance with the target ; λ =wavelength of the signal;
σ = radar cross-section of the target.

1.2.2.7. Pulse repetition time (PRT)

The pulse repetition time (PRT) is the time needed, so they system will be able to send a pulse and receive and echo before sending the next one.

This PRT will determine the changes on the frequency in the emitted signal along with the period of the control voltage at the input of the Voltage Controlled Oscillator.

1.2.2.8. Range [7].

The range of the radar is the maximum distance where a target can be located. Knowing that the pulses will travel from the radar to the target's location and all the way back, then the range can be determine using the velocity of the waves transmitted and the time that goes from the transmission of the pulse till the reception of the echo.

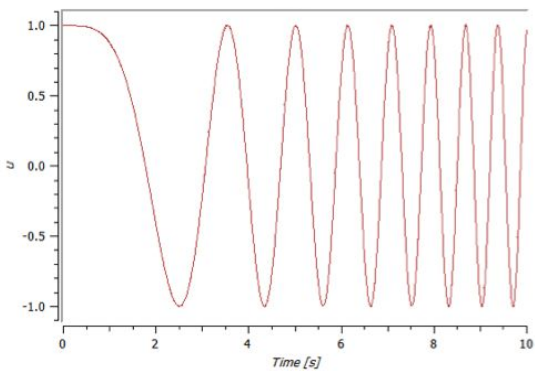
$$R_{max} = \frac{c_0 * (PRT - P_W)}{2} \tag{2.4}$$

1.2.2.9. Chirp signal

A chirp signal is a wave which frequency increases or decreases with the time while other properties of the signal stay constant. It is commonly used in radar or sonar but it has many other applications.

In order to be able to detect the targets in different distances and speeds, it's needed to generate a signal that can propagate with its frequency increasing with the time. This aspect will make possible that this signal can reach targets far away enough with enough power in its signal.

The chirp signal will propagate in a bandwidth specified by the Voltage Controlled Oscillator that will be included in the design. The amplitude of this signal will be determined by the input generator, the gain of the oscillator and also the attenuation of the filter.



Graph 2.1. Chirp signal waveform.

The objective of a radar system, as it has been said before, is to detect targets in the surrounding media and determine their size, angle, speed and distance.
For this matter, a special signal needs to be generate and it will be radiated to the surrounding space.
This signal will consist in a pulse with high energy and long duration. This pulse will help to determine the distance of the target by calculating the time difference between transmitted and received pulse.
However, Doppler frequency or speed of the target will not be determined using this pulse. For that reason, an intermodulation should be introduced, a modulated signal inside this pulse that will allow to compute the Doppler frequency. In this case, the modulated signal introduce is a chirp signal.
The phase difference in the chirp signal will help determine the Doppler frequency and the speed of the target.

Some other parameters from the components of the radar need to be considered such as the antenna effective aperture or gain, the power transmitted by the emitter block or the bandwidth and power of the noise in the system.
All these parameters will be described in each block, in order to have a clearer vision of where they come from.
For further information about any of this parameters, check MIT course about basics in radar [5] or the following radar tutorial [7].

2. Radar design

As presented in previous lines, a radar is a device that creates power pulses in the transmission bandwidth and transmitted them into the surrounding media. The transmitted pulses reflect into the object and obstacles and generate and echo that will be captured by the receiver block. The echo pulse will be transform and modulated in order to fit in the bandwidth of observation and analyse so it will be possible to described the surrounding obstacles and calculated its size and range.

2.1. MIT (Massachusetts Institute of Technology) design. [6]

As it is been said before, the MIT course “ *Build a Small Radar System Capable of Sensing Range, Doppler, and Synthetic Aperture Radar Imaging*”[6] will be the basis for this study.

In this course, the basic principles of the radar system are explained, so using this knowledge it will be possible to construct the same radar as its constructed at the end of the course.

The implemented radar is a Synthetic Aperture Radar (SAR). A radar with a narrow beamwidth antenna, high resolution and gain. Following a certain path, the radar emits pulses, reflected in the ground or the targets in the way and received by the receiver antenna. The echo pulses received are analysed using some algorithms so all the information will be combine to get the spectrum and image of the surroundings.

For this purpose, the block scheme will be the one exhibited in Figure 2.2.

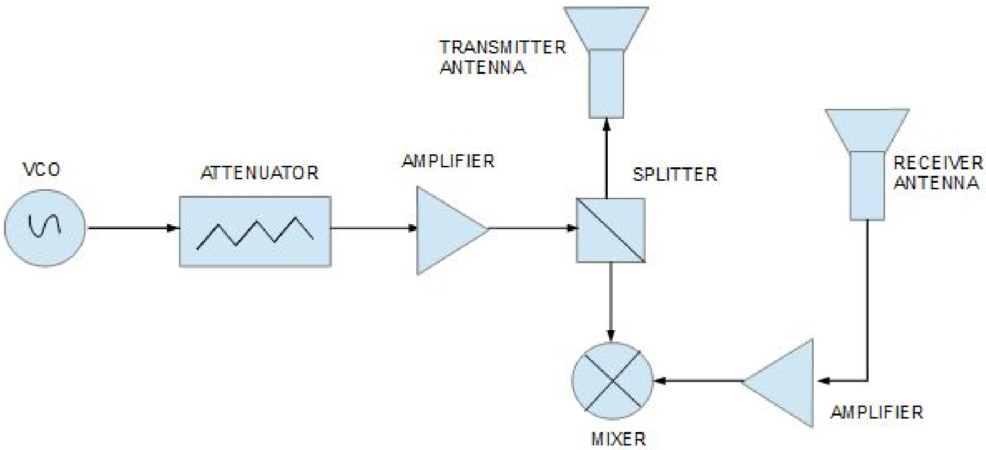


Figure 2.2. Block scheme of MIT radar system.

In this system, the VCO (Voltage Controlled Oscillator) generates a chirp signal, which changes its frequency in time according to the parameters of the oscillator.

To protect the amplifier from saturating, the attenuator reduces the power coming from the VCO. After this, the amplifier increases the power of the signal in order to have the best power level for the transmitted signal at the antenna.

The echo coming from the targets surrounding the system is absorbed by the receiver antenna. In the MIT system design, the antenna is implemented using a can with an aperture in one side and a black hole in the opposite one. The transmission and reception are done using a monopole wire (Microwave Connector (Amphenol P/N: 901-9889-RFX, SMA bulkhead receptacle jack)) according to the specifications included in the documentation for the course.

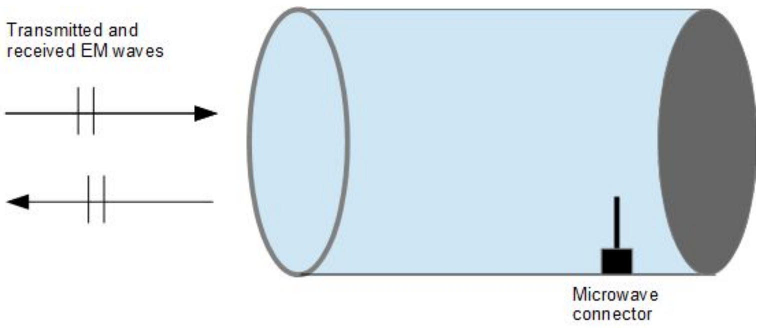


Figure 2.3. Block scheme of antenna used in MIT system.

This signal is amplified by a low noise amplifier and given as an input to a mixer. From the transmitted signal, a sample is taken to the mixer and used as an input port along with the received signal. The operations computed inside the mixer will give a lower frequency and higher power in the output port in order to be analysed by the computer is meant to receive it.

To obtain all the samples in the SAR radar, the system will be connected to a rail that moves it along a certain path. The radar sends pulses and takes samples every 2 seconds. Those samples are sent to the computer where the algorithm is computed to obtain "the final picture".

2.2. Our design.

At the beginning of this study, the radar was intended to be similar as the one implemented in the MIT course. [6]
The analysis of this system leads us to the conclusion that the MIT system can be improved by many ways in order to reduce the noise, improve the range, the transmitted power and the isolation between blocks and antennas.

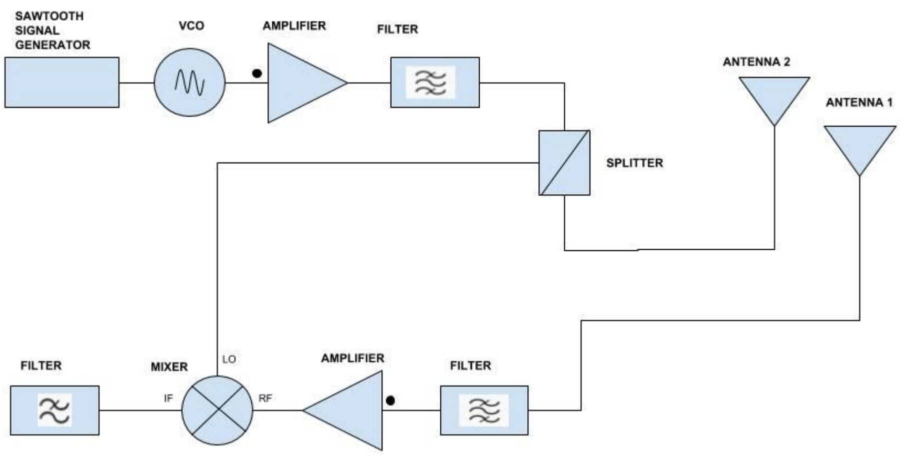


Figure 2.4. Block scheme of the radar system.

It was necessary to add some new blocks in order to improve the design . The bandpass filter in the receiver block preserves our bandwidth reducing the noise level and echoes in other frequencies along the spectrum.

The computer that can substitute the spectrum analysed can only analyse signals up to 20 kHz of frequency, so it is necessary to use a low pass filter to preserve the frequencies in that bandwidth and strongly attenuate the rest.
At this point, after testing some of the components, it was necessary to improve the isolation between systems and antennas. So at the end, a 3dB hybrid is used for the connection between blocks and antennas, giving us the following system to implement.

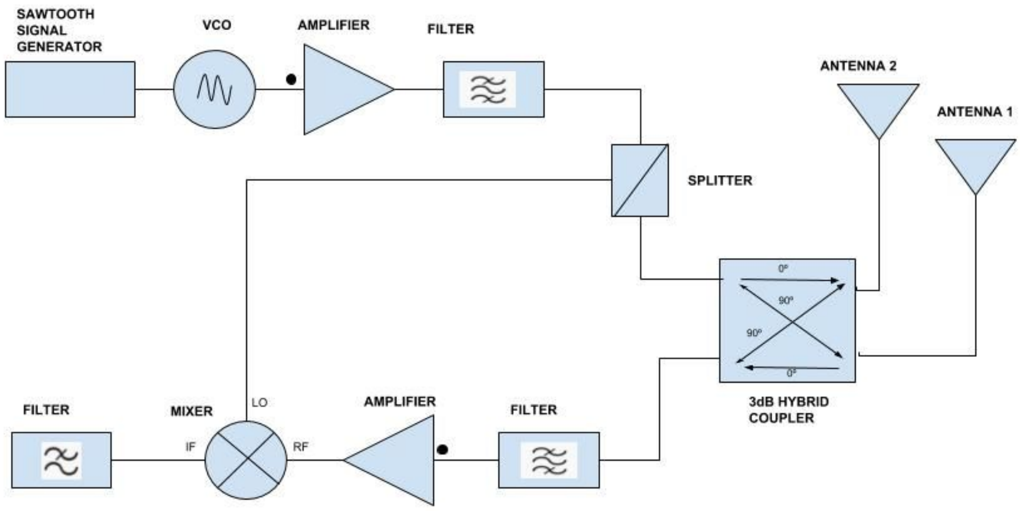


Figure 2.5. Block scheme of the implemented radar system.

In this system, both antennas are emitting and receiving pulses and they will be connected to the transmitted and coupled port of the hybrid. The isolation between the ports connected to the antennas and the ones connected to the transmitter and receiver blocks will be maximum due to the configuration of this 4 port network.

For the analysis and design of this system, we divide it in blocks with different functions and characteristics. The following paragraphs of this chapter will present each block of the radar described.

3. Radar blocks.

As presented in *Figure 2.6* the radar is divided in three main blocks: transmitter, in charge of generation of the pulses and modulated signal; the block in charge of transmission and reception of the wave; and the receiver, in charge of the adaptation of the signal for his latter analysis.

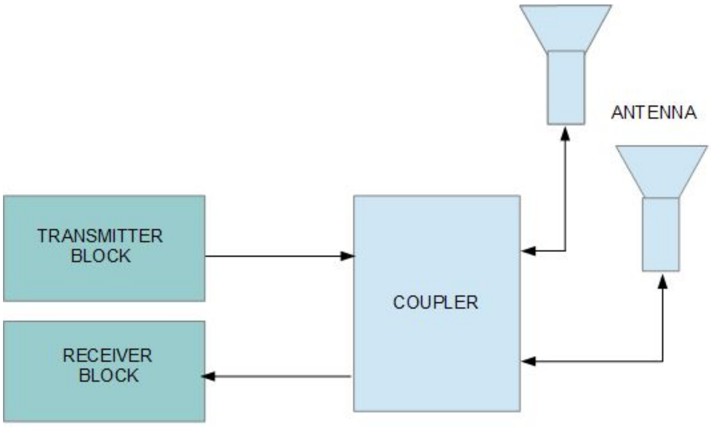


Figure 2.6. Block division for the radar

In the following lines, the block division is going to be analysed along with the function of each of them in the system.

3.1. Transmitter block

The main purpose for the transmitter block is to generate a chirp signal that will work as modulated signal for the pulses sent all over the surrounding space.

As it's shown in the Figure 2.7 the transmitter block has four elements on it.

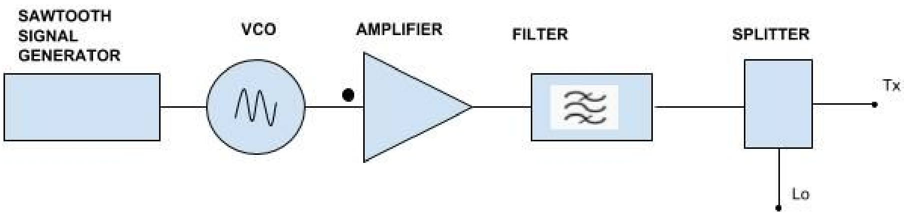


Figure 2.7. Transmission block

The VCO generates a signal that changes in frequency along time depending on the value of its input ports. At its output, it will generate a signal similar to the one shown in the *Graph 2.1.*

The amplifier will modify the amplitude of the signal. It will also add some intermodulation products and nonlinearities that we will describe an analyse in the following chapter.

The signal will need to be attenuated for frequencies outside the free band of the spectrum and for that purpose, a passband filter will be designed. This passband filter is meant to isolate the power coming out from our system from the frequencies outside the free band in the radiofrequency spectrum, so the transmission will be limit to the bandwidth from 2.093 to 2.9Ghz, the free band defined by CNA. [4]

3.2. Signal emission and reception.

As it is been described previously in this chapter, the transmitting block generates a chirp signal that changes in frequency along time. This signal propagates through space by two antennas connected to the transmitter and receiver block.
Once the signal emitted reaches a target, it generates an echo that is detected by these antennas.
The receiver block modifies some aspects of this signal such as its bandwidth and its power so it could be analyse by the spectrum analyser or some other devices designed for this aim.

The system is meant to transmit and receive the signal generated. For that reason it is necessary to use a device capable of emitting and propagating this signal such as an antenna.

According to the initial system designed, one of the antennas would be connected to the transmitting block and it would only radiate the power from the transmitted pulses. The other antenna would be connected to the receiving block and it would only receive the echo that reflects from the target.

The chirp signal at the transmitter block induces a current on the antenna that generates electromagnetic radiation. This radiation goes from the antenna and reflects off the objects surrounding the antenna.
This echo signal goes back to the antenna and induce a current on it generating a signal that is going to be analysed by the receiver block.

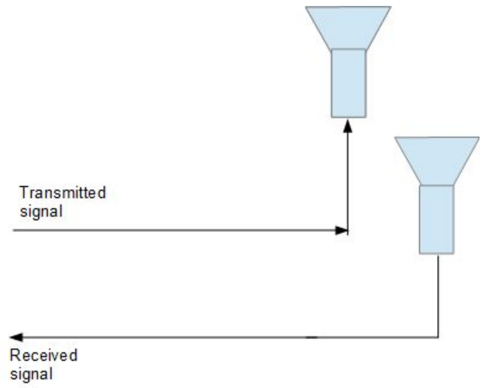


Figure 2.8. Initial block for signal emission and reception.

It is necessary to analyse this design in order to determine the interference and coupling between the two antennas, transmitter and receiver. The antennas, due to their closeness, couple one to another creating ghost in the spectrum of detection. This ghost are false detected targets that can't be allowed in the bandwidth of detection.

The coupling between the antennas would saturate the receiver. The transmitter, a high power block, generates and send pulses through its antenna. The receiver is a sensitive block and it receives the pulses and also the coupled power from the other antenna. This phenomena could saturate it making the receiver unavailable during the transition time back from saturation mode. During this time when the receiver is unavailable, the echoes coming to the antenna don't reach the receiver so the radar misses these targets.
For that reason, it is important to reduce the coupling between antennas to the minimum so no information would be lost at the receiver.

For that reason, as illustrated in Figure 2.9, a new block is designed with the purpose of improving the isolation between antennas and the transmission and reception blocks.

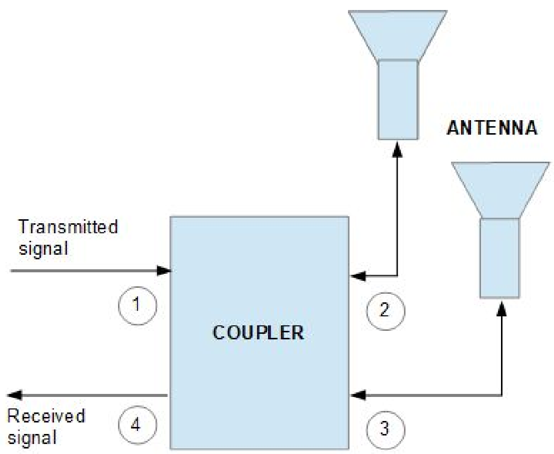


Figure 2.9. Block for signal emission and reception.

The new system has both antennas transmitting and receiving, so a linear array is created. This structure increases the directivity of the antennas due to the array disposition.
The directional coupler used in this system minimises the coupling between the antennas and, at the same time improves its connection with receiver and transmitter blocks. The directional coupler isolates its input and isolated ports, the ones that in our design are identified as the ports connected to the transmitter and receiver blocks.
The transmitted and coupled ports of the coupler are also isolated by this disposition, so it does not exist any coupling between the two antennas.
This design will solve the problem of the low directivity of the antennas and the coupling between them. The quality of the system will be increased and also the detection of the targets in the surrounding space.

3.3. Receiver block.

Once an optimum signal is been received, the receiver block needs to adapt it in order to make it possible for the computer to analyse it.

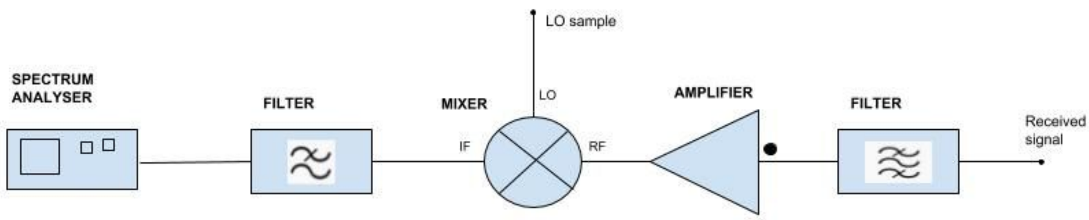


Figure 2.10. Reception block

First of all, the signal received goes through a bandpass filter that limits the bandwidth of the signal to the one we are analysing and attenuate it to prevent the saturation of the amplifier.

The attenuation and the low level of power received make indispensable the amplification of the power in the signal. An amplifier is going to be used for that purpose. This component, reduces the level of noise in the spectrum and amplifies the power in the signal.

For all calculations related with distance, velocity or size of the target, it is necessary to compute the difference between the local oscillator sample frequency and the frequency of the received signal. A mixer performs this operation and makes possible for us to determine the characteristics of the target.
The capacity of the audio recorder in the computer is usually close to 20 Khz so it is be necessary to filter this signal to reduce its bandwidth.
MIT system design uses an algorithm that combines all pulses received in a certain period of time. This program could be used for our radar results in order to improve the accuracy of detection

Chapter 3

Design of the main components of the radar

As it was explained in the previous chapter, the radar system can be divided in three blocks: transmitter, receiver and the block meant for the radiation and reception of the wave. These blocks are constructed using components that will be designed and implemented in order to provide the best characteristics to the system they are part of.

The goal for this system is to be able to detect targets in medium-short distance. To achieve this, the power of the transmitted signal and the receiver isolation from noise need to be maximum.

The following chapter will describe the behaviour and design of all components for the radar system designed. These components will be tested in order to determine their real performance in the radar system.

1. Voltage Controlled Oscillator.

A Voltage Controlled Oscillator, VCO, is a component whose oscillation frequency is controlled and modified by an input voltage source called tuning voltage.

1.1. Behaviour and main parameters of a VCO.

The oscillation frequency and the output signal, as it is shown in *Figure 3.1,* depend not only on the value of the tuning voltage but also on the value of the resistors and capacitance in the circuit. For further information about VCO behaviour and working principles, give a look to [13].

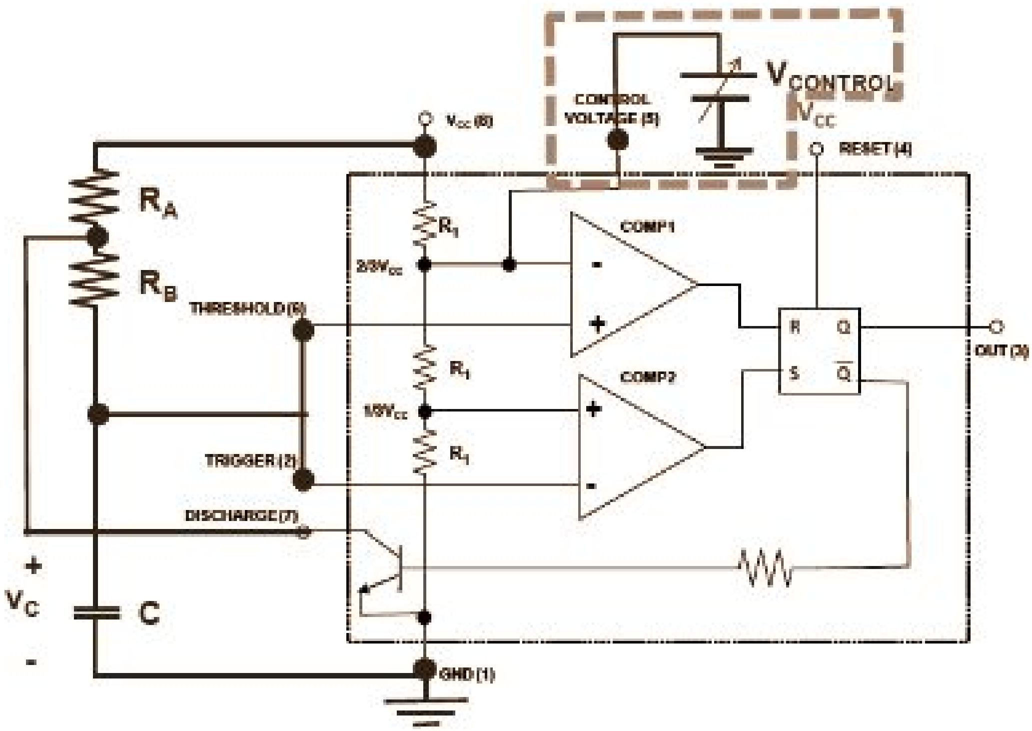


Figure 3.1. Circuit scheme of a Voltage Controlled Oscillator from slides[12]

The following paragraphs will describe some important aspects and parameters needed for the analysis of this component. Nevertheless, its design as a component is not going to be explained. The level of abstraction is raised to system level, analysing only input and output signals and losses that may occur.

1.1.1. Free oscillation frequency.

The free oscillation frequency is the working frequency of the oscillator under no external influence. In this case, it will be reached for a tuning voltage equal to cero.

1.1.2. Tuning voltage.

The tuning voltage modifies the frequency on the output signal of the oscillator, by following *Formula 3.1.*

$$\omega_o[\frac{rad}{s}]=\omega_f[\frac{rad}{s}]+K_o[\frac{rad}{s.V}]\cdot V_e[V] \tag{3.1}$$

where wfr = free oscillation frequency ; Ko = gain of VCO ; Ve = tuning voltage

For a tuning voltage value equal to zero, the frequency of oscillation will be equal to the free oscillation frequency.
The changes on frequency will be linear along with changes in voltage, in a range defined from the maximum to the minimum frequency established by manufacturer.

1.1.3. Phase noise

Phase noise represents the amount of signal power at a given sideband or offset frequency from ideal transmission frequency. In radio frequency (RF), phase noise can create a channel-to-channel interference, degrading RF signal quality. It is typically expressed in dBc/Hz.
Its effect will be shown in the following chapters of this study.

1.2. The VCO of the radar system.

The component chosen to generate the chirp signal in this system is a Voltage Controlled Oscillator (VCO). The VCO, as mentioned before, changes the frequency of its output signal depending on the value at its tuning voltage pin.
The manufacturer specifies some characteristic, shown in Chart 3.1., that will need to be tested during the design of the circuit.

PERFORMANCE SPECIFICATION	MIN	TYP	MAX	UNITS
Lower Frequency:			2328	MHz
Upper Frequency:	2536			MHz
Tuning Voltage:	0.5		4.5	VDC
Supply Voltage:	4.75	5.0	5.25	VDC
Output Power:	+5.0	+7.0	+9.0	dBm
Supply Current:		20	35	mA
Harmonic Suppression (2^{nd} Harmonic):		-15	-10	dBc
Pushing:			1.5	MHz/V
Pulling, all Phases:			1.5	MHz pk-pk
Tuning Sensitivity:		78		MHz/V
Phase Noise @ 10kHz offset:		-105	-101	dBc/Hz
Phase Noise @ 100kHz offset:		-126		dBc/Hz
Load Impedance:		50		Ω
Input Capacitance:			15	pF
Operating Temperature Range:	-40		+85	°C
Storage Temperature Range:	-45		+90	°C

Chart 3.1. VCO main parameters values indicated by manufacturer [11]

The VCO is provided a sawtooth signal that will work as tuning voltage. This source that varies from 0.5 to 4.5V produces changes in frequency in the output signal that goes from 2324 to 2536 Mhz.

According to the manufacturer,the power will be equal to 7 dBm in all the transmission band . The 2nd order intermodulation product (IP2) will introduce some tones in other frequencies of the spectrum causing distortion and dividing the output power of our VCO between them and the transmitted one. This effect will be minimised later with the filter designed and the amplification of the power in our transmitting band.

1.3. Test of the component.

1.3.1. Simulation of the component using AWR.

The circuit simulated in order to obtain the response for the parameters in Chart 3.1 is shown in Figure 3.2. The model of VCO available in AWR software only allow us to introduce Phase noise and tuning voltage parameters in order to simulate. The final results for the simulation of this component would be shown, as with all the rest of them, in laboratory.

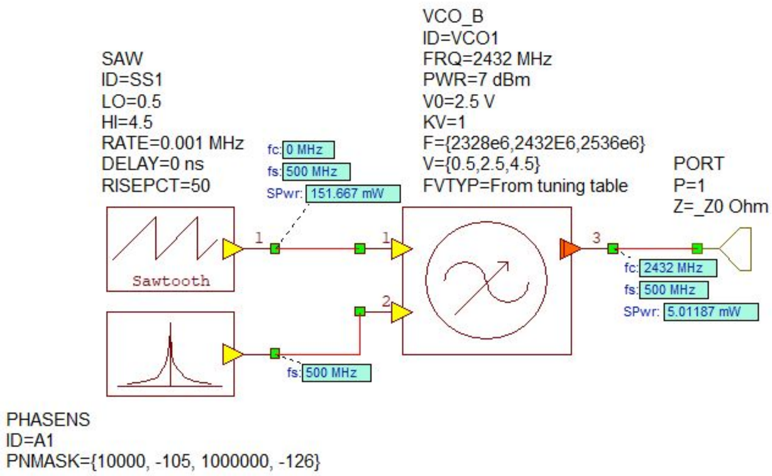
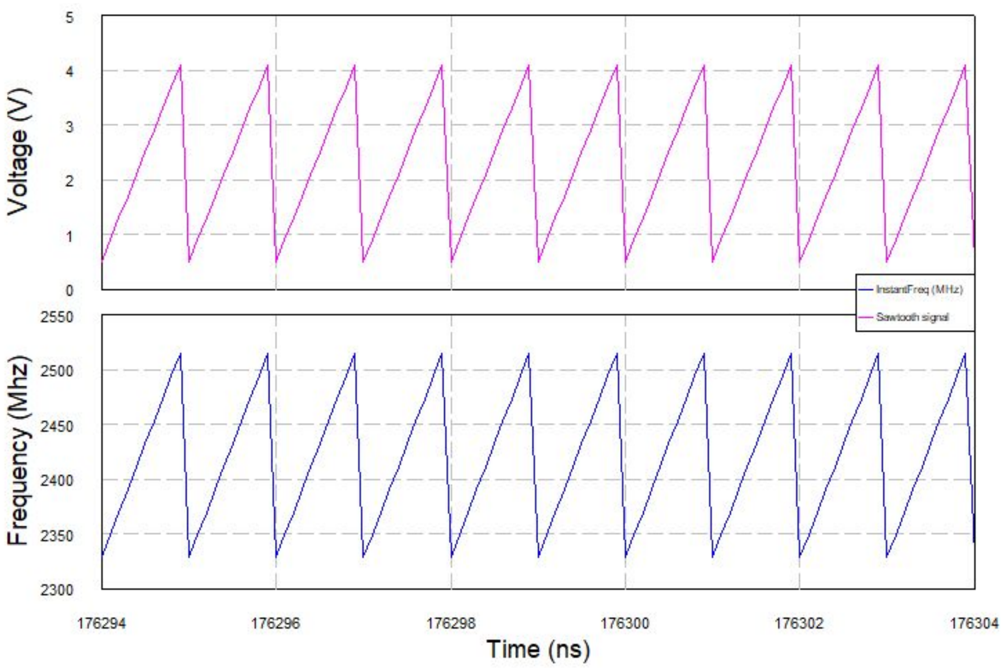


Figure 3.2. Circuit of VCO in AWR simulator

The system shown in Figure 3.2. generates the following chirp signal whose frequency variations along with tuning voltage can be seen below in Graph 3.1.



Graph 3.1. .Input sawtooth signal for the VCO and output signal of f=2432 Mhz

The changes in frequency at the output of VCO goes along with the linear variation of the voltage signal provided at the tuning voltage pin.

1.3.2. Protoshield design of the component.

The protoshield design ot the VCO is necessary for its test in laboratory. The following circuit is an implementation of the one given by the manufacturer for construction and simulation of this Voltage Controlled Oscillator VC0555.

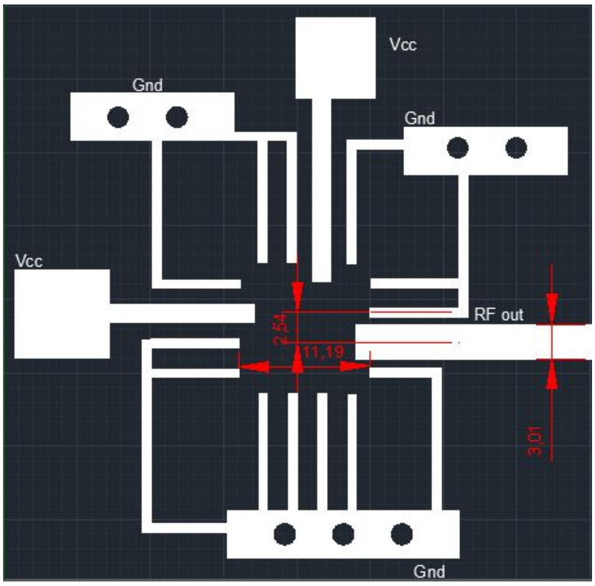


Figure 3,3, Autocad Design VCO555

2. Amplifier

An amplifier is a component that increases the power at its input by multiplying it by a parameter called gain. It does not make any changes in frequency of the signal but the intermodulation products and noise can affect to its spectrum of the signal.

2.1. Behaviour and main parameters of an Amplifier

Here are shown and explained some of the main parameters and characteristics of an amplifier. For further information about amplifier features go to [1; Ch. 12].

2.1.1. Gain

The input signal is multiplied by a parameter called gain, characteristic of the amplifier. If we reach the point of nonlinearity in power, the amplifier's gain starts to be non-linear.

$$Pout[dBm] = Pin[dBm] + G[dB] \tag{3.2}$$

2.1.2. Output power saturation.

The output power saturation is the maximum amount of power the amplifier can have at its output port. When the amplifier reaches the point of maximum power, it saturates and stops amplifying the signal at its input.

2.1.3. Intermodulation products.

The intermodulation products are generated by nonlinear behaviour of the amplifier. When more than one tone is placed at the input of the amplifier, their interference produces more tones in different frequencies result of the linear combination of them.. There are two types of intermodulation product depending of the linear combination applied.
Second order intermodulation products (IP2) are the result of the linear combination $f1+f2 \quad or \quad |f1-f2|$ whereas third order intermodulation products (IP3) are the result of linear combination $2*f1+f2$, $f1+2*f2$, $|f1-2*f2| \quad or \quad |2*f1-f2|$

The power of those tones will be calculated applying Formula 3.3.

$$P_{m,n}[dB]=X+(|m|+|n|)\cdot Pin \qquad (3.3)$$

2.1.4. 1 dB Power compression (P1dB)

Due to the saturation of the amplifier, the linearity of the curve Pin/Pout decreases when we reach high values of the Pin.

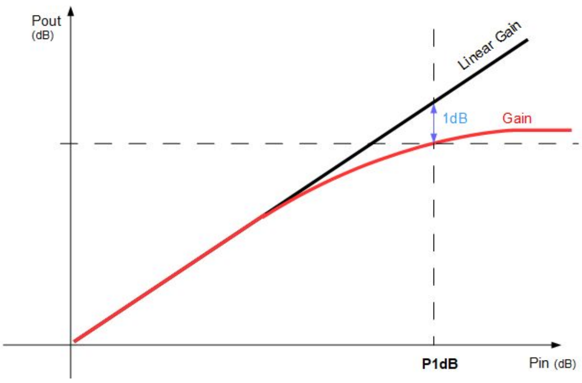


Figure 3.4. P1dB effect in gain.

The value of input power when the difference from the linearity reaches 1 dB is called 1 dB compression point (P1dB).

2.1.5. Noise figure (NF)

Noise figure is the degradation of the SNR caused by the amplifier in the radio frequency(RF) signal chain.

$$F = \frac{\mathrm{SNR_{in}}}{\mathrm{SNR_{out}}} \tag{3.4}$$

2.2. The amplifiers of the radar system.

For this step, an amplifier ERA-5 is going to be used. According to the manufacturer, we expect to find the following characteristics on it.

MODEL◆ NO.	⊙ FREQ. GHz	GAIN , dB Typical								MAXIMUM POWER (dBm) at 2 GHz*			DYNAMIC RANGE at 2 GHz*		VSWR (:1) Typ.				ABSO-LUTE MAX. RATING[3]		DC OPERATING POWER[4] at Pin 3			
		over frequency, GHz								Output (1 dB Comp.)		Input (no dmg)	NF (dB)	IP3 (dBm)	In		Out					Device Volt.		
	f_L-f_U	0.1	1	2	3	4	6	8	Min.@ 2 GHz	Typ.	Min.		Typ.	Typ.	DC-3 GHz	3-f_U** GHz	DC-3 GHz	3-f_U** GHz	I (mA)	P (mW)	Current (mA)	Typ	Min	Max
ERA-6	DC-4	12.6	12.5	12.2	11.7	11.3	—	—	10.5	17.9	16	20	4.5	36	1.3	1.2	1.6	1.8	120	650	70	5.0	4.6	5.6
ERA-4	DC-4	14.3	14.0	13.4	12.7	11.8	—	—	11	17.3	15	20	4.2	34	1.2	1.2	1.3	1.8	120	650	65	4.5	4.2	5.5
ERA-5	DC-4	20.2	19.5	18.5	17.3	16.2	—	—	16	18.4	16.5	13	4.3	32.5	1.3	1.3	1.2	1.3	120	650	65	4.9	4.2	5.5

Chart 3.2. Amplifier main parameters values indicated by manufacturer [10]

Values shown in Chart 3.2 are significant values of the amplifier and they need to be tested in the laboratory using real components.

In its documents, the manufacturer recommends to use the amplifier with scheme shown in Figure 3.5.. It is necessary to test this circuit scheme to see the effect and parameters given.

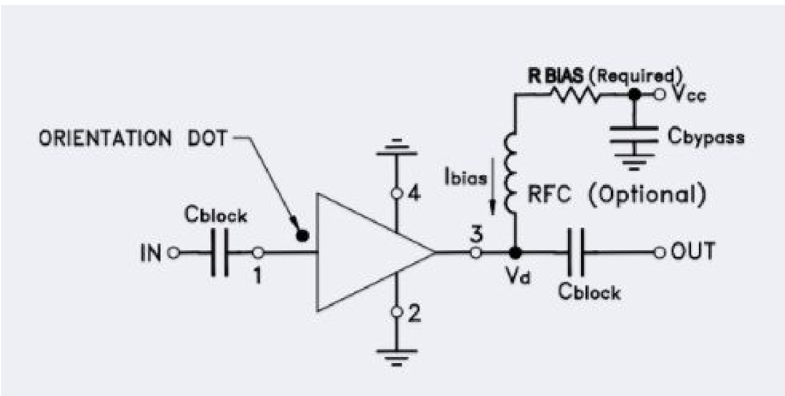


Figure 3.5. Amplifier circuit from manufacturer specifications[10]

Each element in the circuit has a purpose. Capacitors isolate the amplifier from the DC current that can reach it and cause distortion. Under this circumstances, capacitors act like an open circuit. The inductor isolates the amplifier from the higher frequencies coming to or from the output of this device. It acts like an open circuit in the presence of these high frequencies.

For designing this system in a protoshield as simple as possible, a transmission line is going to be used to isolate the RF from the DC voltage source that feeds the amplifier as it is shown in Figure 3.6.
The inductor is replaced by a transmission line of high impedance followed by two branches. The first branch is followed by a resistance and a DC voltage source whereas the other one would be a capacitor connected to ground.

In this case, to make this design more simple, the capacitor will be substituted by a transmission line with length equal to λ/4. The short circuit that will be placed in the point of connection with the resistance will be transform in an open circuit at the end of this line.

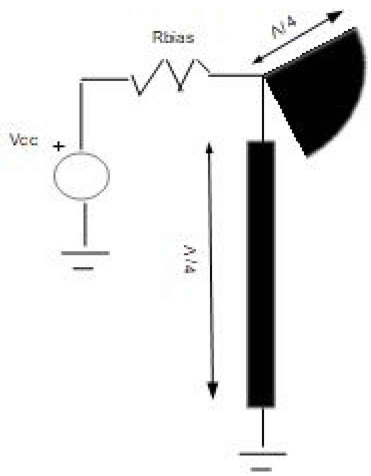


Figure 3.6 Transmission line circuit for RF and DC isolation.

In order to choose the width of this transmission line, it is necessary to compute some calculations. A line of maximum impedance can isolate RF from DC voltage and the other way around. A transmission line of maximum impedance is the one with the minimum width.
Due to the limitations of the design imposed by the protoshield, the minimum width is 100um.
The impedance for a transmission line of that width is 166.1 ohms
Knowing that the accuracy for the construction is +-50 um , the width of the line will be 500 um and its impedance 109.227 ohms.

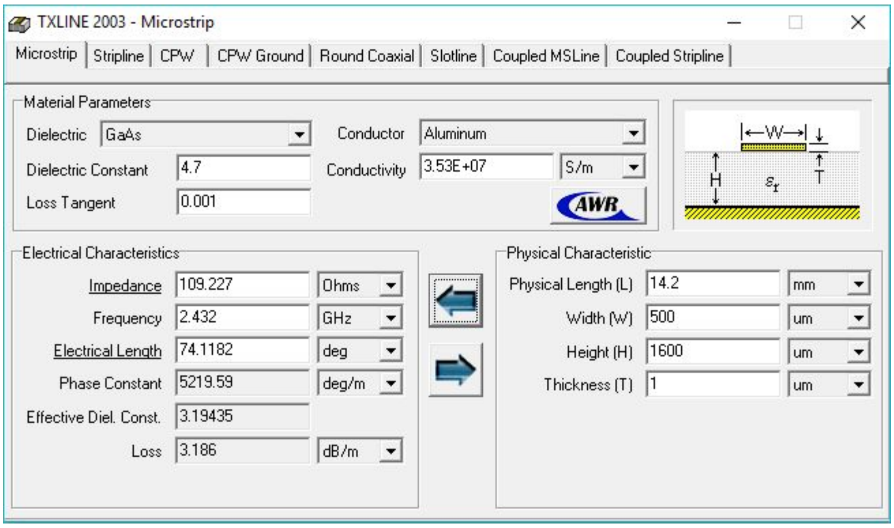


Figure 3.7. External applications. AWR Calculations for transmission lines.

The analysis of the network shown in Figure 3.6 will require its transformation in an equivalent RF problem as the one shown in Figure 3.8. In this scheme, the transmission line connected to an impedance Z_l will correspond to the output of the amplifier, and the stub connected to it will be equivalent to the circuit shown before.

The following calculations are trying to place an open circuit at the input of this stub as it corresponds for the isolation between RF and DC.

The stub has a length of λ/4 and the equivalence between the propagation constant and the wavelength, we obtain the following equivalence to use in the input impedance formula of the stub.

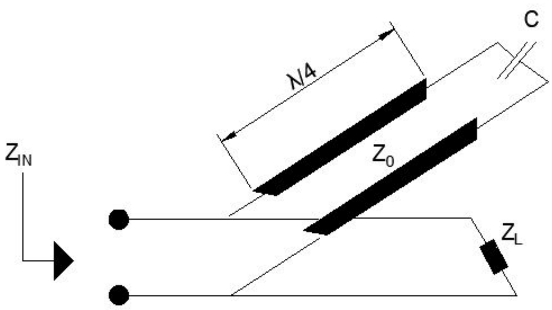


Figure 3.8.Transmission line impedance calculations circuit.

The input impedance Z_{in} of the circuit in Figure 3.8 should be close to 50 ohm. Furthermore, the impedance of the stub calculated before in Figure 3.7 should be high enough for this system to show an open circuit.

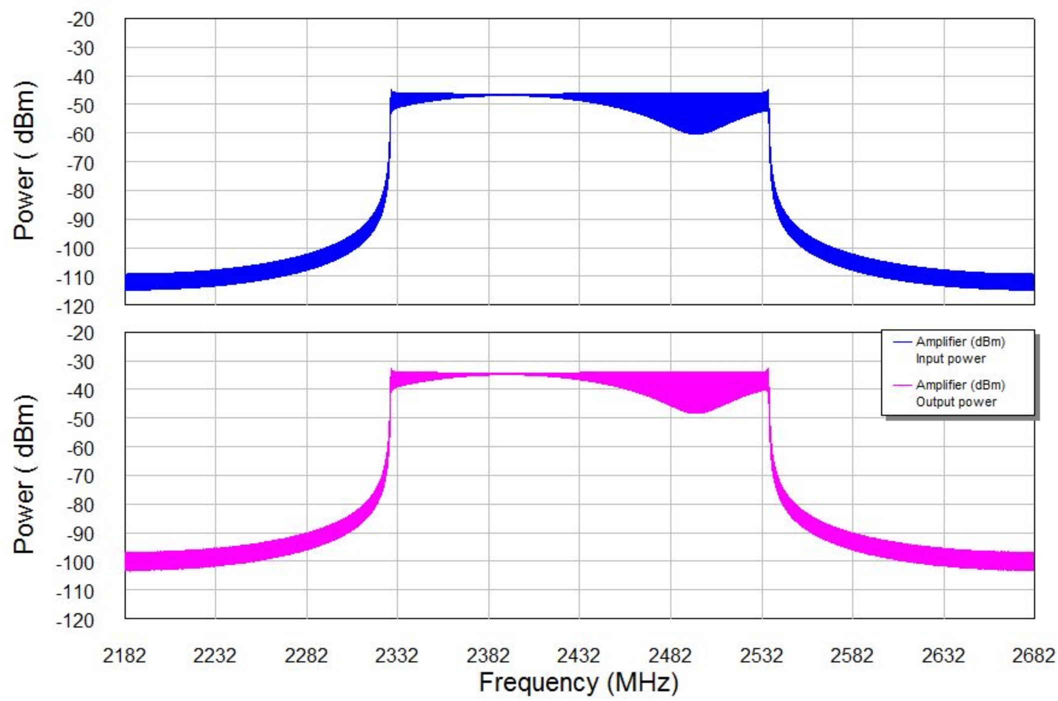
Being aware that the length of the transmission line at the stub is λ/4, its impedance 109 ohms and the value of the capacitor 100nF, the input impedance of the stub is equal to Z_{stub}=j6.7e6 ohms

The parallel connection between Z_l and Z_{stub} will give an input impedance for this line equal to 50 ohm. From the output of the amplifier, it will be seen as an open circuit for the DC but it will let the RF pass through it.

2.3. Test of the component.

2.3.1. Simulation of the component using AWR.

The power response of the VCO simulated at AWR Design Environment using general components is an almost ideal signal with no interference or noise. However as we introduce all characteristics of the amplifier, such as second and third order interferences, it is possible to see that more tones appear in other ranges of frequencies, the amplifier saturates at a certain power level or the gain is not linear for a given input power.

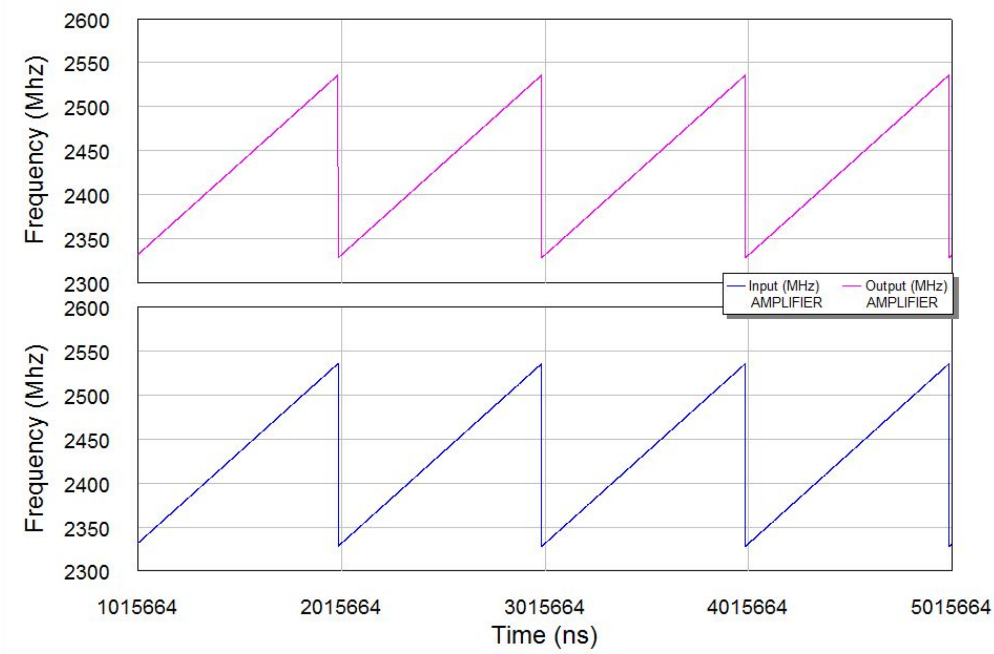


Graph 3.2. . Input and Output power spectrum of the amplifier (dBm)

As shown in Graph 3.2, the 7 dBm of power at the output of the VCO are added to the gain of the amplifier, 18.5dB. In an ideal device, the final signal would have a greater output power, but some parameters of the amplifier such as IP3, P1dB or NF (values shown in Chart 3.1), make this device less linear and more vulnerable to noise and other interferences.

During the design, it would be important to make P1dB as big as possible. That would indicate that these nonlinearities are introduced at bigger input power levels.

However, the component used was not design by us and its characteristics were given by the manufacturer in Chart 3.2.



Graph 3.3.. Input and output instant frequency at the amplifier

The amplifier, as it can be appreciated in Graph 3.3, doesn't modify the bandwidth of propagation and preserves the one specified by the VCO used.

2.3.2. Protoshield design of the component.

Before testing the component in the laboratory, we need to design the protoshield we will use.

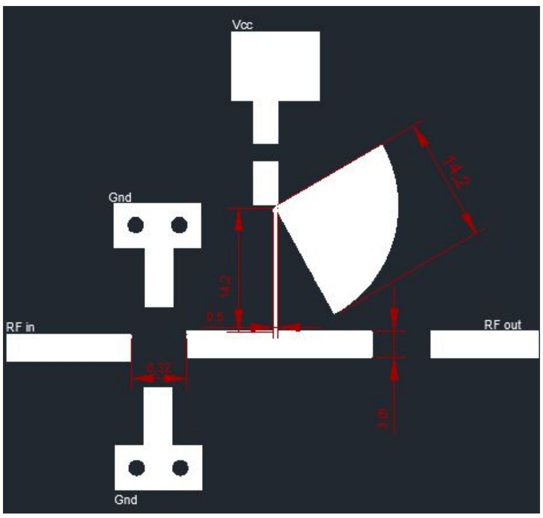


Figure 3.9. Autocad Design. Amplifier

3. Filter

As explained by Pozar [1], “*a filter is a two port network used to control the frequency response at a certain point in an RF or microwave system by providing transmission at frequencies within the passband of the filter and attenuation in the stopband of the filter.* ”

3.1. Behaviour and main parameters of the filter.

3.1.1. Main parameters.

The following paragraphs show the basic parameters to consider in order to design and simulate a filter.

3.1.1.1. Attenuated and protected band.

The protected band of the spectrum is the group of frequencies that have the lowest attenuation and that it’s meant to have maximum power at the output of the filter.

The attenuated band of the spectrum is meant to have the lowest amount of power.

3.1.1.2. Mask of the filters.

It’s the representation of the amount of attenuation along the frequencies in the spectrum. It represents the attenuation on dB’s in the y’s exes and the frequencies in the x’s exes.

3.1.1.3. Attenuation

Amount of power that will be subtracted to the output of the filter and that frequently has different values for each frequency.
It’s defined by the filter’s equation[14] and represented by the curve draw by this equation.

3.1.1.4. Poles and zeros

Poles are values in frequency that creates zeros on the denominator of the equation of our filter.

Zeros are values in frequency that creates zeros on the numerator of the filter's equation.[14]

3.1.1.5. Order of the filter.

It's the quantity that defines the accuracy of the filter. It's given by the calculation of maximum between poles and zeros in the filter equation.[14]
The order of the filter determines also the number of elements or coupled lines that will necessary in order to implement the filter.

3.1.1.6. Ripple

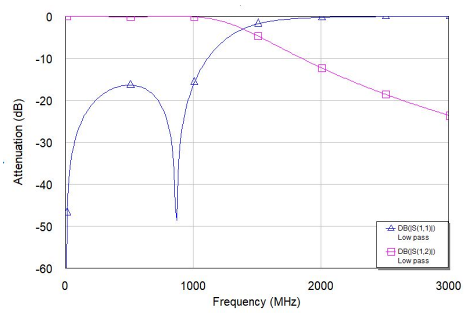
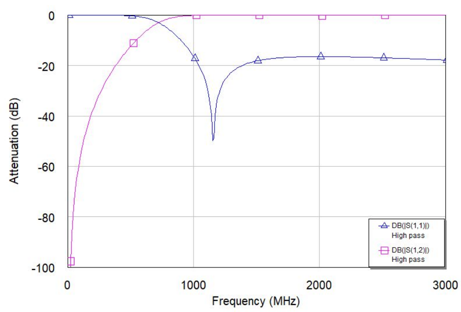
It's the wave of amplitude equal to the ripple value that it's generated in the protected band of Chebyshev filters.

3.1.2. Types of filters

Filters can be classified depending on different factors that will change their design and construction.

3.1.2.1. Depending on its frequency response

Filters could be classified by its frequency response. These are the types of filter commonly used or implemented depending on the frequencies attenuated or saved :

Low pass filter	High pass filter.
	
The protected band goes from zero to an specified frequency and attenuates the rest.	It attenuates the frequencies from zero to an specified frequency and passes the rest.

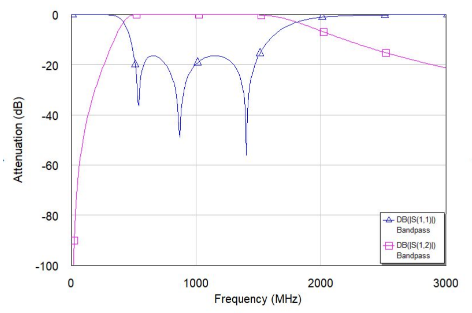
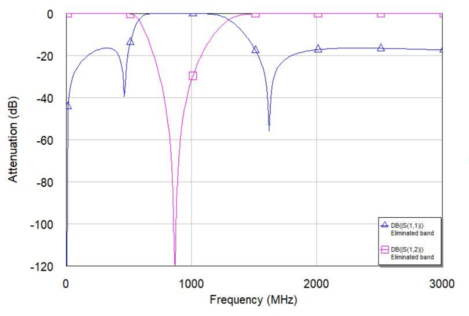
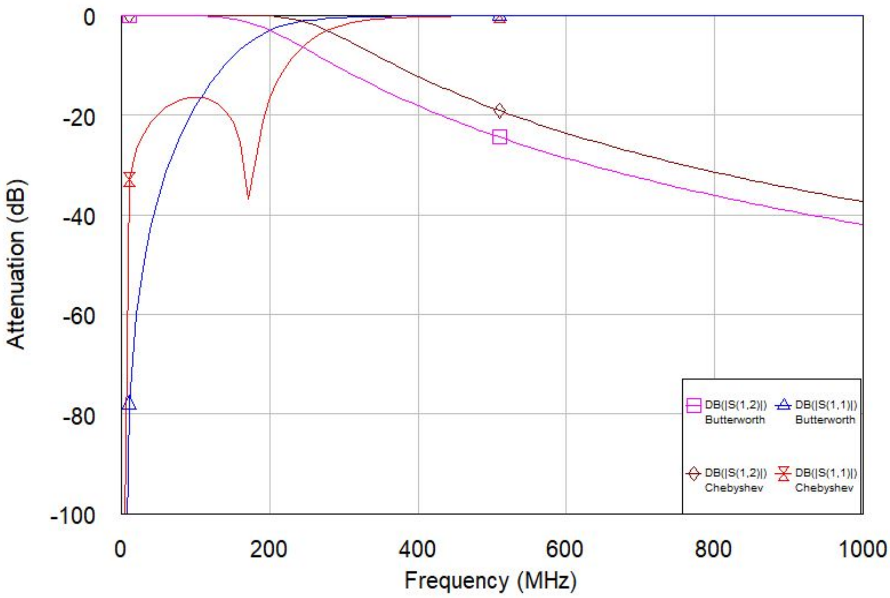
Bandpass filter	Eliminated band filter
	
It attenuates all the frequencies out of the protected band.	It attenuates only an specified band of frequencies and allows the rest.

Figure 3.10. Types of filters depending on frequency response

3.1.2.2. Depending on its specifications

Depending on its specifications and on the simplicity of the design, there are different approximations such as Chebyshev, Butterworth, Bessel, Gaussian or some others.

The most suitable ones for this system are Chebyshev and Butterworth and they will be characterized in the following lines.



Graph 3.4. Transformation of frequencies to LP filter.

In Graph 3.4., the Chebyshev filter has bigger ripple in the passband but also it reaches zero as a lower frequency. For a ripple equal to zero, the response of the Chebyshev filter is maximally flat so it becomes a Butterworth design.

For further information about Chebyshev and Butterworth approximation and their characteristics give a look to [1; Ch.8].

3.1.3. Design of a filter

Chebyshev filters appear to be more suitable for radar design due to its accuracy and the simplicity of its design. Depending on its mask, the design and implementation changes.

For the design of the bandpass filter, it is necessary to calculate parameters of the filters such as bandwidth and central frequency. The mask of the bandpass filter is transformed into low pass filter one.

$$B=\frac{(2\cdot\pi\cdot f_{p1}-2\cdot\pi\cdot f_{p2})}{w_{p'}} \tag{3.5}$$

where fp1, fp2 : limits of bandpass of the filter ; wp' = 1 rad/s.

$$w_o=\sqrt{w_{p1}\cdot w_{p2}}=\sqrt{(2\cdot\pi\cdot f_{p1})\cdot(2\cdot\pi\cdot f_{p2})} \tag{3.6}$$

where fp1, fp2 : limits of bandpass of the filter ;

Frequencies of the band-pass filter are transformed to low-pass filter frequencies, using the following formula, where fa is the limit of the attenuated band of the filter.

$$w_a=\left|\left(\frac{w_o}{B}\right)\cdot\left[\left(\frac{2\cdot\pi\cdot f_a}{w_o}\right)-\left(\frac{w_o}{2\cdot\pi\cdot f_a}\right)\right]\right| \tag{3.7}$$

For the design of low pass filters, it is be necessary to transform the frequencies, nevertheless the calculations for now on, are performed in the same way for low-pass and band-pass filter.

$$k_s=\frac{1}{w_{a'}} \qquad k_p=\sqrt{\frac{10^{\frac{\alpha_c}{10}}-1}{10^{\frac{\alpha_p}{10}}-1}} \tag{3.8}$$

where wa : limit of the attenuated band of LP filter; α_c : attenuation in attenuated band of the filter ; α_p : attenuation in passband of the filter.

The value of the order of the filter is calculated using this formula. The order of the filter determines the number of passive elements or the number of coupled lines that are needed to construct the filter.

For Chebyshev filter the order of the filter will be equal to the value obtained applying Formula 3.9.

$$n_C = \frac{aarcosh(\frac{1}{k_d})}{aarcosh(\frac{1}{k_s})} \tag{3.9}$$

As for the lowpass filter the order of the filter will be n_c, in a bandpass filter will be equal to $2n_c$

In the case of lumped elements design, the number of components for a bandpass filter will be equal to *2n*, being *n* the order of the filter. For low pass filters, the number of passive elements will be equal to *n*

In the case of coupled lines design, the number of transmission lines will be equal to $n + 1$ for both designs.

3.1.3.1. Concentrate elements.

The design of the filter will look like *Figure 3.11* depending on the order of the constructed filter.

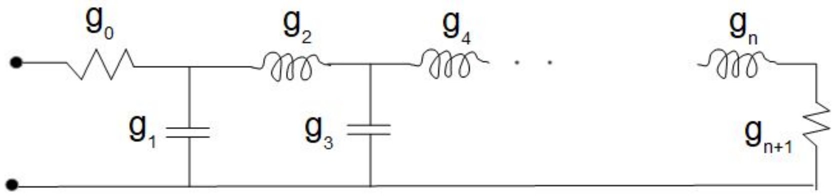


Figure 3.11. Transformation of frequencies to LP filter.

The value of these elements will be given by normalised charts that contains normalised values for $g_0 = g_{n+1} = 1$. [1: Ch.8]

The relation applied to denormalized the elements will be related with the frequency of the protected band of the lowpass filter wn and also to the value of the impedance R_0.This denormalization will provide commercial values that the designer will be able to buy or construct.In the Figure 3.12 is shown the equivalent circuit for a low pass filter.

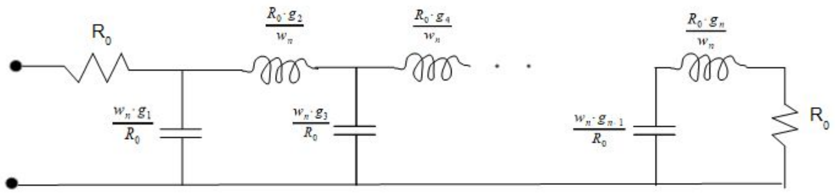


Figure 3.12. Denormalization of values for LP filter design.

In order too have equivalent circuit for band-pass filter, each element of the filter will be transformed by performing the following operation.

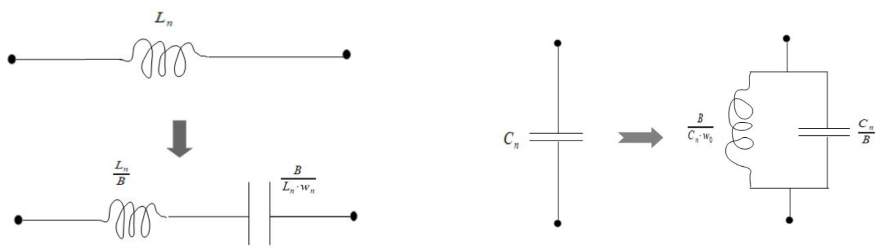


Figure 3.13. Transformation of elements from LP to BP filter.

3.1.3.2. Coupled transmission lines design.

The coupled transmission lines design is determined by the values g_n obtained for each parameter of the filter. It will be necessary to compute the parameters JZo for each element of this elements.

$$
\begin{aligned}
Z_0 J_1 &= \sqrt{\frac{\pi \Delta}{2 g_1}} \\
Z_0 J_n &= \frac{\pi \Delta}{\sqrt{2 g_{n-1} g_n}} \; para\, n = 2,3,\ldots,N \\
Z_0 J_{N+1} &= \sqrt{\frac{\pi \Delta}{2 g_N g_{N+1}}}
\end{aligned}
\tag{3.10}
$$

Once calculated the value of this parameters, the even and odd impedance associated to each of them can be calculated by using Formula 3.11.

$$
\begin{aligned}
Z_{oe} &= Z_o[1 + JZ_o + (JZ_o)^2] \\
Z_{0o} &= Z_o[1 - JZ_o + (JZ_o)^2]
\end{aligned}
\tag{3.11}
$$

The width and the separation between each of the lines is computed by the simulation of the circuits shown in Figure 3.14. The input impedance of the even and odd circuits need to be the one calculated previously.
However, the measurements of the coupled lines may be adjust in order to obtain a more suitable response from the filter designed.

All design explained step by step is shown in [1; pp.430-436].

Even mode circuit	Odd mode circuit

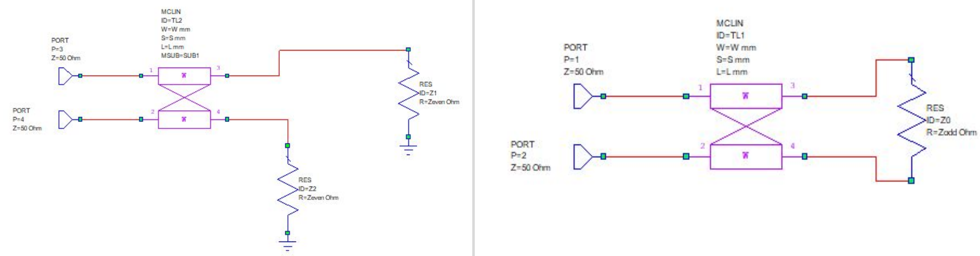


Figure 3.14. Simulation odd and even mode of a transmission line.

3.2. The passband filter of radar system.

The information found on the CNA website specifies that the free band available for our radar in the spectrum goes from 2.035 to 2.93 GHz. At the moment, it is not important to isolate the transmitted signal from all sources of distortion but to isolate the non-free band of the spectrum from the emitted signal.

This filter is implemented in order to prevent the non free part of spectrum from harmonics, noise or other suitable sources of distortion that the signal may have. It is important to remember that the bandwidth of transmission includes frequencies from 2.3 to 2.5 Ghz and that's the band that needs to be protected.

The filter chosen for implementation is a Chebyshev filter. Its passband includes frequencies from 2.2 Ghz to 2.9 Ghz and the attenuation suffered by these frequencies is approximately 1dB. The rest of frequencies below 1.95 Ghz and above 2.9 Ghz is strongly attenuated with a 20dB factor. Nevertheless, the attenuation in all spectrum is conditioned by the ripple of this filter that has been fixed to 0.1 dB. The final mask of the filter, result of all these conditions can be seen in Figure 3.15.

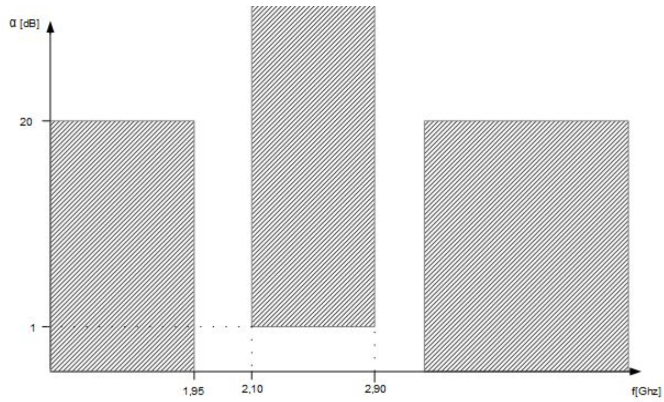


Figure 3.15. Transformation of frequencies to LP filter.

3.2.1. Design of the filter.

The first step for the design of the filter is to calculate the bandwidth and the central frequency by using the formulas listed in previous pages.

According to Formula 3.6 the bandwidth calculates it 4.389 Grad/s, that is equivalent to 0.7 Ghz in terms of frequency. The central frequency of the filter, chosen for the conversion of frequencies from bandpass to lowpass filter, is equal to 15870 Mrad/s as shown in Formula 3.7.

These two parameters determine the mask of the equivalent low pass filter. The limit of the passband for the lowpass filter is equal to wp = 1 rad/s , and using Formula 3.8 the initial limit frequency for attenuated band obtained is 1.88 rad/s

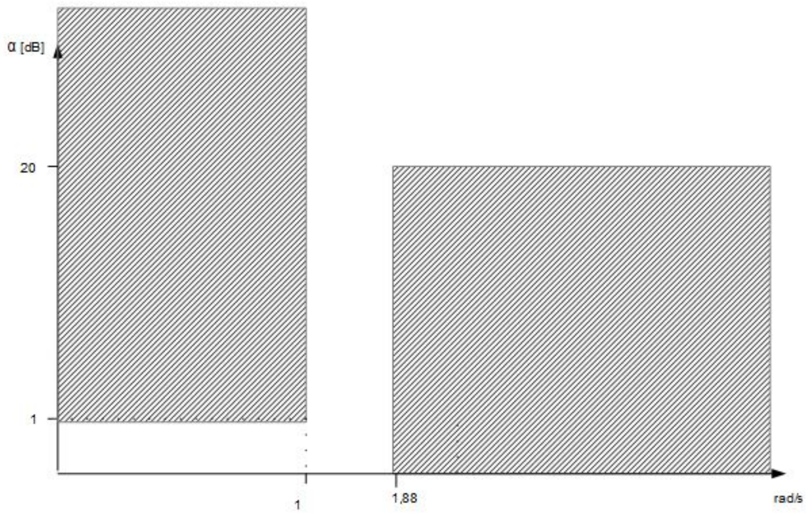


Figure 3.16. Transformation of frequencies to LP filter.

Once the mask of the lowpass filter is chosen and design, it is necessary to obtain the order of the filter in order to implement it whether using lumped elements or coupled lines.
Using Formula 3.8. the discrimination and selectivity values obtained for the Chebyshev filter are kp = 0.05114161 and ks = 0.529582.
Applying Formula 3.9. and the values obtained in the previous calculation, the value of the order of the filter calculated is 2.9327 that for design and construction should be taken as 3. However, Chebyshev design for a passband filter has order twice this value so it will be 6.

There are two possibilities for designing this filter. It could either be designed use passive elements that increase losses and make the filter more expensive or it could be designed using coupled lines technology. This kind of design decrease the losses and attenuation produce but increase the size of the circuit representing the filter.

Even if both procedures will be simulated and calculated, for this kind of filter the most suitable design is the coupled lines design due to its lower losses and distortion. However, it is necessary to consider the size of the circuit after all this procedure, so it is not a circuit too big for construction.

Calculations for passive elements design.

The design of the filter includes 6 inductors and capacitors and also 2 impedances with 50 ohms value. The values come from the Chebyshev charts used for this ripple and its transformation performed as shown in Figure 3.12 for a bandpass filter.
Applying these transformations, the values shown in Chart 3.3 are obtained for the filter elements.

gn	Value	R0	Element	Denormalized value	Passband filter elements		
					C'n	L'n	R'n
g0	1	50	R		-	-	50
g1	0,7156938	50	C	0,014313876	3,25E-12	1,22E-09	-
g2	1,5348954	50	L	76,74477	2,28E-13	1,74E-08	-
g3	1,2529130	50	C	0,02505826	5,70E-12	6,98E-10	-
g5	1	50	R		-	-	50

Chart 3.3. Elements of the passband filter.

Calculations for transmission lines design.

To design the filter using this technology, it is necessary to determine the width, length and separation between coupled lines.

The dielectric FR4 used for this construction has the following characteristics: Er =4.7 ; T = 1um ; H = 1.6 mm. It's necessary to specify this in order to calculate W, L and S for the transmission lines needed.

	g1	g2	g3	g4
W (mm)	2.02	4.54	4.54	2.02
S (mm)	0.162	0.249	0.249	0.162
L (mm)	15.55	15	15	15.55

Chart 3.4. Elements of the passband filter (coupled lines)

The calculations performed in order to calculate this parameters were done using Formulas 3.11 and 3.12 and wizard TrxLine from AWR Microwave Simulator like the one shown in Figure 3.7. The whole procedure for calculation and design of the filter using coupled transmission line were explained by Pozar [1; pp.426-436]

3.2.2. Test of the component.

3.2.2.1. Simulation of the component using AWR.

For the lumped elements design, the filter circuit is the one presented in Figure 3.17.

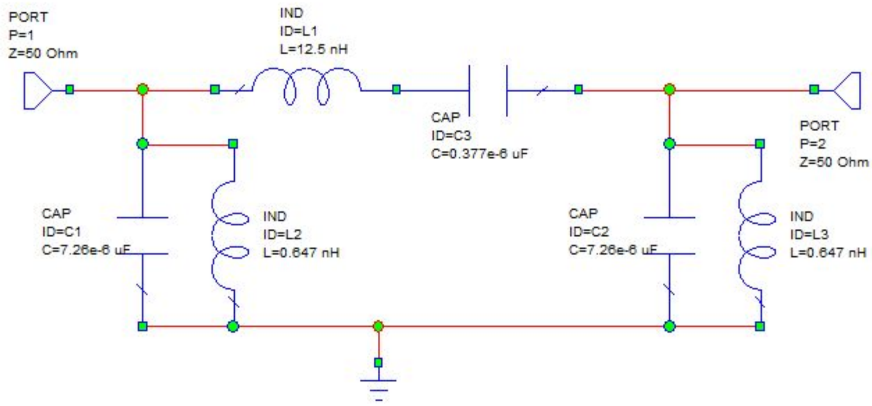
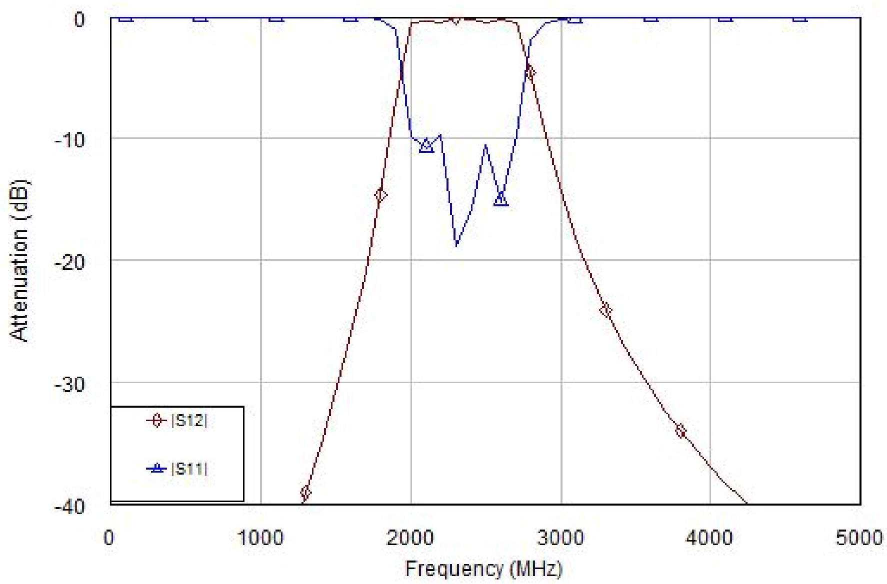


Figure 3.17. Circuit for filter implementation using lumped elements.

Simulating transmission parameters (S11, S12) of this filter, we obtain the following response for our filter.



Graph 3.5. Frequency response(S parameters) of the emitter filter constructed with lumped elements.

The attenuation faced by the signal through this filter is close to 0.5dB in the passband, which gives small attenuation for the frequencies we want to save. The attenuation in the rest of frequencies out of this band is big enough to eliminate their effect. However, the response of this filter could be better by increasing the order of the filter and adding more elements to the circuit.

The response presented is not symmetric in the central frequency of the filter and we can observe that the ripple is not constant and close to -5dB for parameter S11. The next design for this filter, using coupled transmission lines will improve this filter, but it will add more losses and ripple in the passband of our spectrum.

In the following lines the coupled transmission lines designed is simulated. This filter design is implemented in the following circuit using 4 coupled lines as it shows the procedure explained by Pozar [1; pp.432] for the transformation from a lumped elements design to a coupled lines design using resonators.
The following circuit is constructed using values from Chart 3.3.

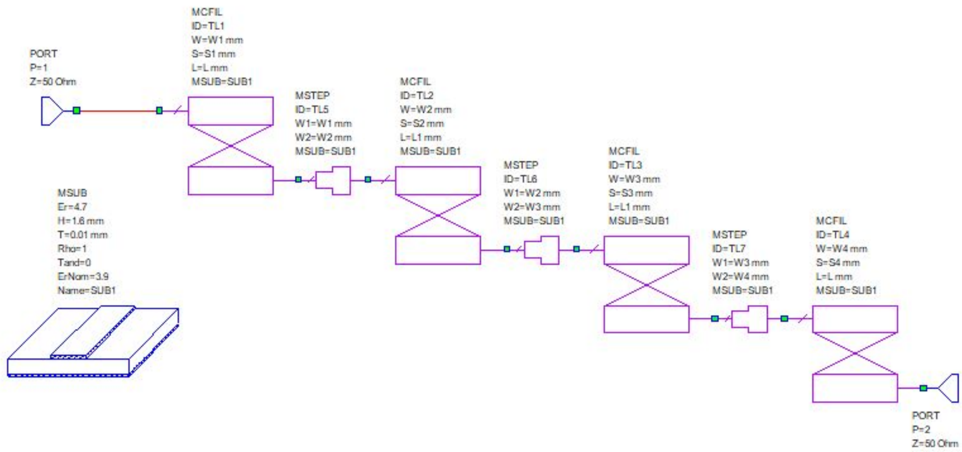
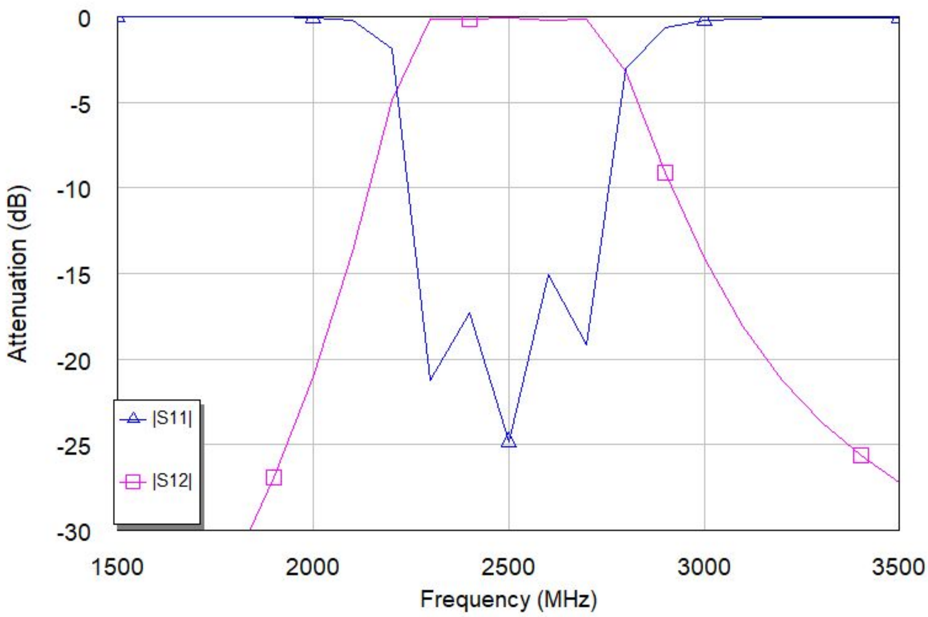


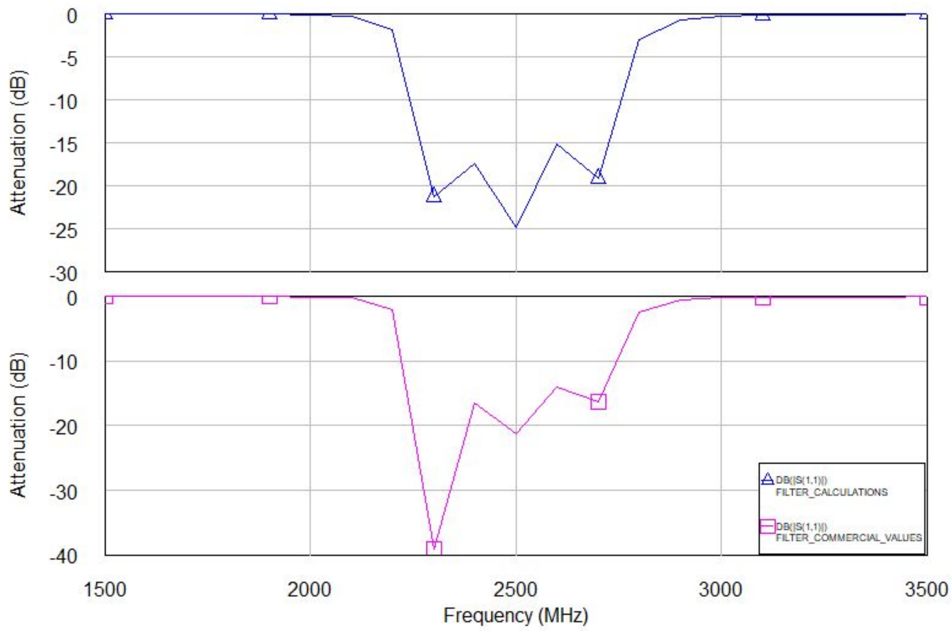
Figure 3.18. Transmission filter with coupled lines.

The attenuation in the passband is closed to the one specified for the design 0.1dB, but we can see that after several iterations adjusting the parameters and values in the coupled lines, we manage to achieve lower losses in this filter, so the parameters S11 for the power reflected from filter is lower than the one shown in the simulation in Graph 3.5.



Graph 3.6. Frequency response (S parameters)
of the emitter filter constructed with lumped elements.

However, it is important to take in count that once it will be constructed, the accuracy of construction goes around +-50um . This will change the mask of the filter in the following way .



Graph 3.7. Filter masks with normalised and calculated values.

Even after adding this 50um to every measurement in the coupled lines of the filter, the mask is good enough to be used as filter.

3.2.2.2. Protoshield design of the component.

We are going to implement the design with coupled transmission lines. Its response, as we shown before, is better than the filter implemented using lumped elements. Before testing the component in the laboratory, we need to design the protoshield we will use.

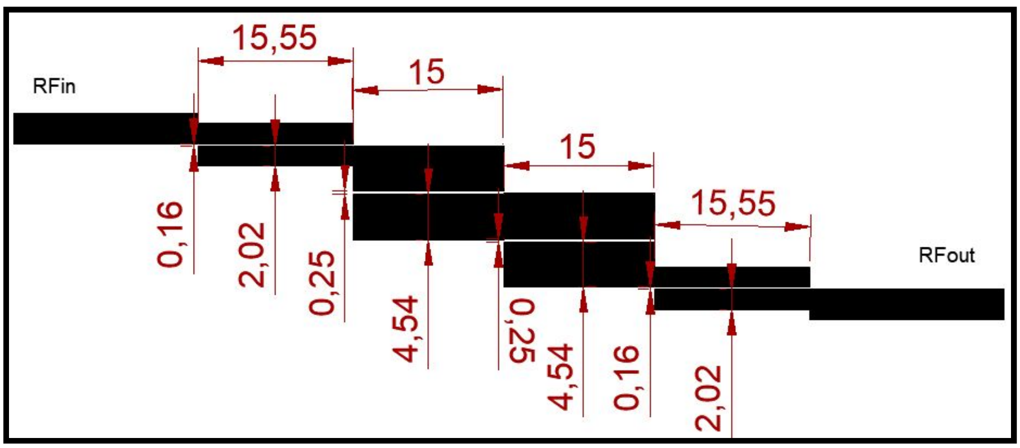


Figure 3.19. Autocad design of the bandpass filter.

3.3. The low pass filter of the radar system.

The computer that processes all the echoes received from targets limits the bandwidth of the signal analysed to 20Khz. However, the mixer only limits IF signal frequency to 800 Mhz what could cause damage in all systems at the computer. For this reason, it is necessary to limit the bandwidth of the spectrum to the 20Khz that could be analyse.
A low-pass filter will save the frequencies from 0 to 20Khz and attenuate the rest of frequencies in the spectrum.

3.3.1. Design of the filter.

The first step in the filter design is the determination of the mascara and the approximation that are going to be used.

The Chebyshev design will fit better to the specifications of the filter. Frequencies and attenuation levels will be determined according to the specifications mentioned before.

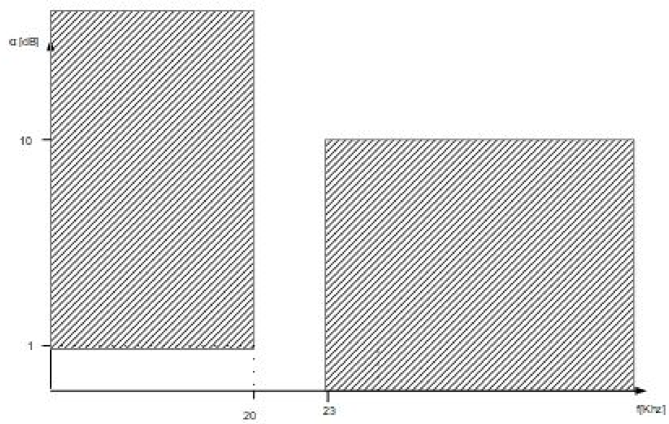


Figure 3.20. Mask of low pass filter.

The mask of the filter with the specifications mentioned before is shown in the Figure 3.20.
Using a variation of formulas 3.10 for low pass filter, we obtain parameters ks = 0.87 and kd = 0.1696. The order of the filter obtain using this value is 4.54649, that will give as a low pass Chebyshev of order 5. This will mean that the circuit will have 6 concentrate elements, in addition to the 50 ohms input resistances.

g_i		Value		Commercial values
0	1	R	50	**50**
1	1,1468	C	0.183 uF	**0.18 uF**
2	1,3712	L	0.546 mH	**0.56 mH**
3	1,9750	C	0.314 uF	**0.33 uF**
4	1,3712	L	0.546 mH	**0.56 mH**
5	1,1468	C	0.183 uF	**0.18 uF**
6	1	R	50	**50**

Chart 3.5. Element values of low pass filter

3.3.2. Test of the component.

3.3.2.1. Simulation of the component using AWR.

The circuit obtained after all the calculations is the one illustrated in Figure 3.21. It is necessary to consider that the elements obtained in the calculations are not available in the market, so they will need to be normalized and converted to commercial values.

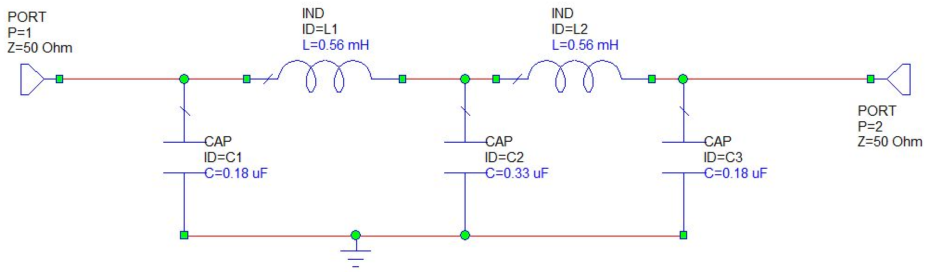
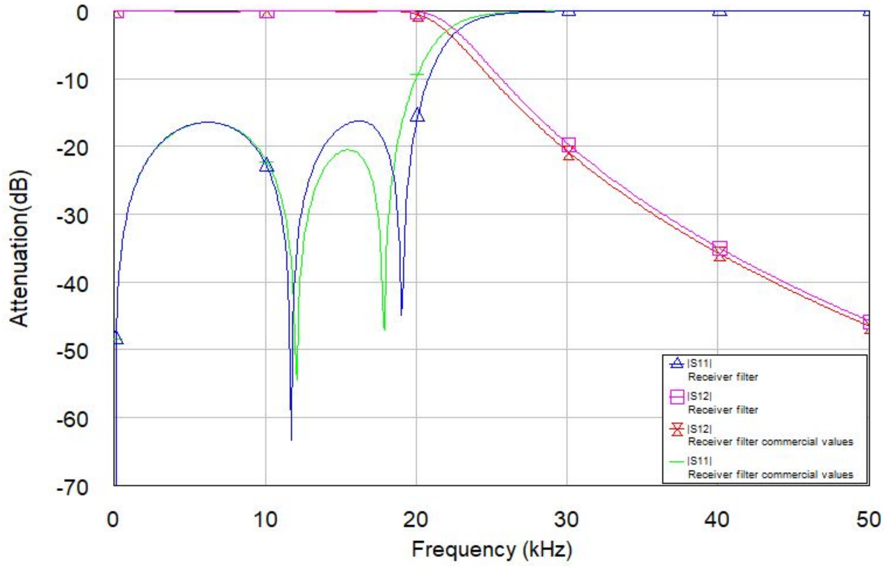


Figure 3.21. Equivalent circuit of low pass filter. - normalised elements

The circuit is simulated to observe the attenuation in the spectrum, especially in the bandwidth of our signal. In this case, it needs minimum attenuation on the pass band so the transmitted signal won't be attenuated in power.
As shown in Graph 3.8, the ripple of the Chebyshev signal is close to 0.1dB. This value is determined by the elements picked from the Chebyshev elements table.



Graph 3.8. Representation of transmission parameters for a low pass filter designed. (calculated and normalised values)

The response of the filter with the calculated elements and the response of the filter with the commercial values are shown in Graph 3.8.

As it's seen there's not such a big difference between the two models. The attenuation in the pass band of both models is smaller than -0.5dB and the attenuated band is bigger than -15dB.So it will be possible to use the concentrate elements design for the filter.

3.3.2.2. Protoshield design of the component.

The filter implemented will be the lumped elements design. The main reason for choosing this one is the high order of this filter and the amount of calculations and circuit size that will be needed in a coupled lines filter like the one shown before.

In order to test this component in the laboratory, it will be necessary to implement it in a protoshield like it is shown in Figure 3.22.

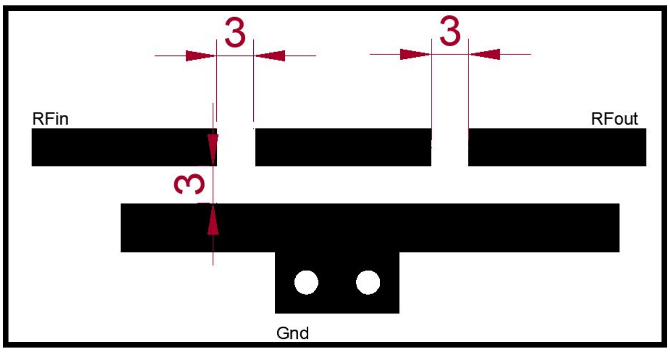


Figure 3.22. Autocad design for LP filter.

4. Mixer

A mixer is a three port component which performs frequency conversion. These three ports are known as : local oscillator (LO), that acts always as an input; radiofrequency (RF) and intermediate frequency (IF) that can act as input or output, depending on the purpose of this mixing.

4.1. Behaviour and main parameters of the VCO.

Mixers translate the frequencies on the input, to a different frequency at the output.
This translation is made by applying the following formulas.

- Downconversion. In case it's necessary to obtain a smaller frequency the mixer computes the difference between the inputs, LO and RF.

$$f_{IF} = |f_{LO} - f_{RF}| \tag{3.12}$$

- Upconversion. In case it's necessary to obtain bigger frequencies, the mixer obtains two frequencies close the local oscillator ones. The inputs are LO and IF, and the output are two RF signals.

$$\begin{aligned} f_{RF1} &= f_{LO} - f_{IF} \\ f_{RF2} &= f_{LO} + f_{IF} \end{aligned} \tag{3.13}$$

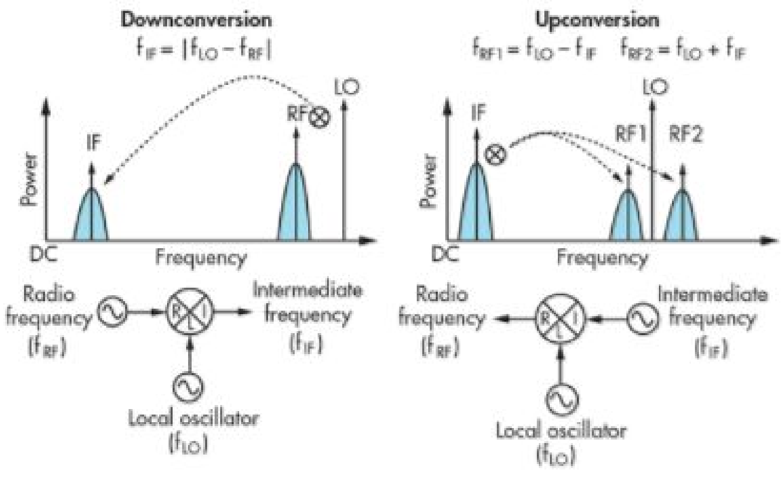


Figure 3.23. Frequency transformation performed at the mixer.

4.1.1. Conversion loss

The conversion loss is defined as the difference between the amplitude of the input signal and the amplitude of the desired output signal.

4.1.2. Isolation

Isolation is the amount of power that leaks from one port to another. If it's higher, the amount of power leaked is low.
In a mixer, it prevents the RF signal and LO signal to interfere so the output signal IF would be as tight as it could in frequency and amplitude as the one expected.

4.1.3. Intermodulation distortion (IP3).

It occurs when two signals get into the mixer's IF or RF input port at the same time. These two signals interfere with each other and with the local oscillator signal, which creates distortion. The interferers obtained at the IF output can be result of linear combination of frequencies shown in Formula 3.14.

$$\begin{aligned} \text{Interferer}_1 &= 2f_{RF1} - f_{RF2} - f_{LO} \\ \text{Interferer}_2 &= 2f_{RF2} - f_{RF1} - f_{LO} \end{aligned} \tag{3.14}$$

These two interferences are too close to IF signal frequency. No amount of filtering can remove these unwanted interferences.

4.2. The mixer of the radar system.

The need of a mixer comes from the relation between maximum bandwidth of the computer analyser and the bandwidth of the signal received from the antenna.

The bottom line is to reach a bandwidth of 20Khz from an original bandwidth close to Gigahertz. The mixer will compute the difference and summation between the signal received (f_{RF}) and the signal from the local oscillator(f_{LO}).

$$f_{IF1} = |f_{RF} - f_{LO}| \qquad f_{IF2} = |f_{RF} + f_{LO}|$$

With the low pass filter f_{IF2} is eliminated because its value would be bigger than the 20Khz limit. .

According to the manufacturer[11], the local oscillator power sample should have a value within -3dBm and 3 dBm. The final value chosen as a sample is 0 dBm.
The manufacturer also limits the frequencies at the ports so local oscillator sample port will be within 2 to 3 Ghz, the frequencies at the RF port will be within 2.0 to 2.7 Ghz. This is the reason why all signals need to be filtered before to fit in these specifications.

Originally, the device computes the multiplication of the RF input power and the LO input power. So, talking in dBm, it will be equivalent to the addition of the power sources.
Since, our RF signal will have different values according to the shape and values of the chirp signal received and targets detected.

4.3. Test of the component.

4.3.1. Simulation of the component using AWR.

For the design of the mixer, the manufacturer[11] gives an application circuit that is evaluated in the following paragraphs so the mixer's performance is suitable for the system.

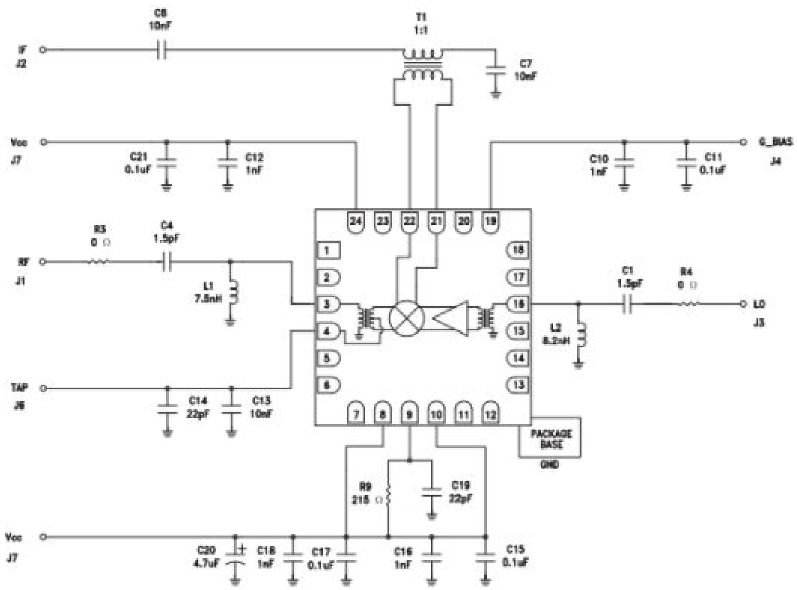


Figure 3.24. Manufacturer specifications for mixer's application circuit. [11]

At LO and RF ports of the mixer, the manufacturer has placed a high pass filter that will limit the frequencies of the incoming signals. However, the filtering of these signals have been already done by the filters of the radar system. It is necessary to evaluate if the frequencies attenuated correspond with the ones attenuated in the mixer's manufacturer design.

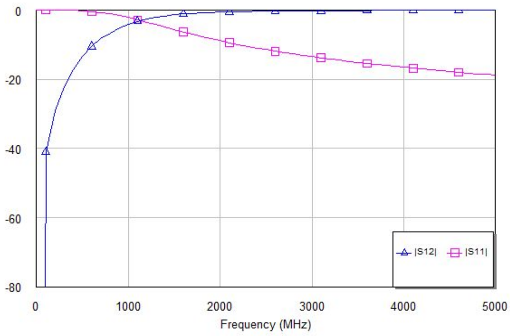


Figure 3.25. Mask of high pass filter at RF mixer input

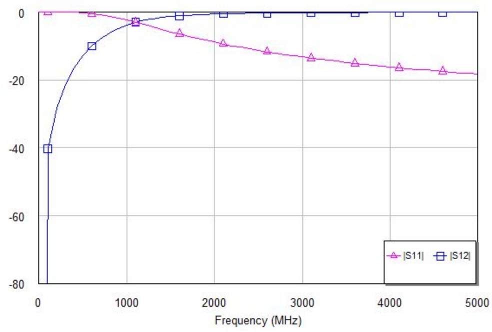


Figure 3.26.Mask of high pass filter at LO mixer input

The manufacturer attenuates frequencies that were already attenuated by the filters in the system so it is not necessary to include them in the circuit of the mixer.

The manufacturer also includes a circuit at the input of the Vcc port as shown in Figure 3.27.

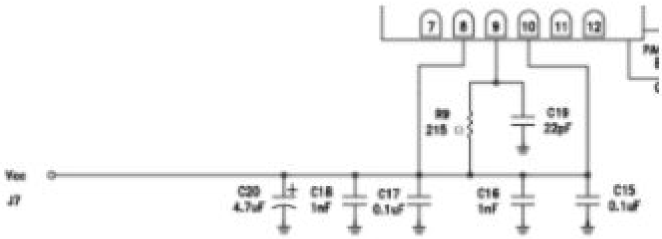
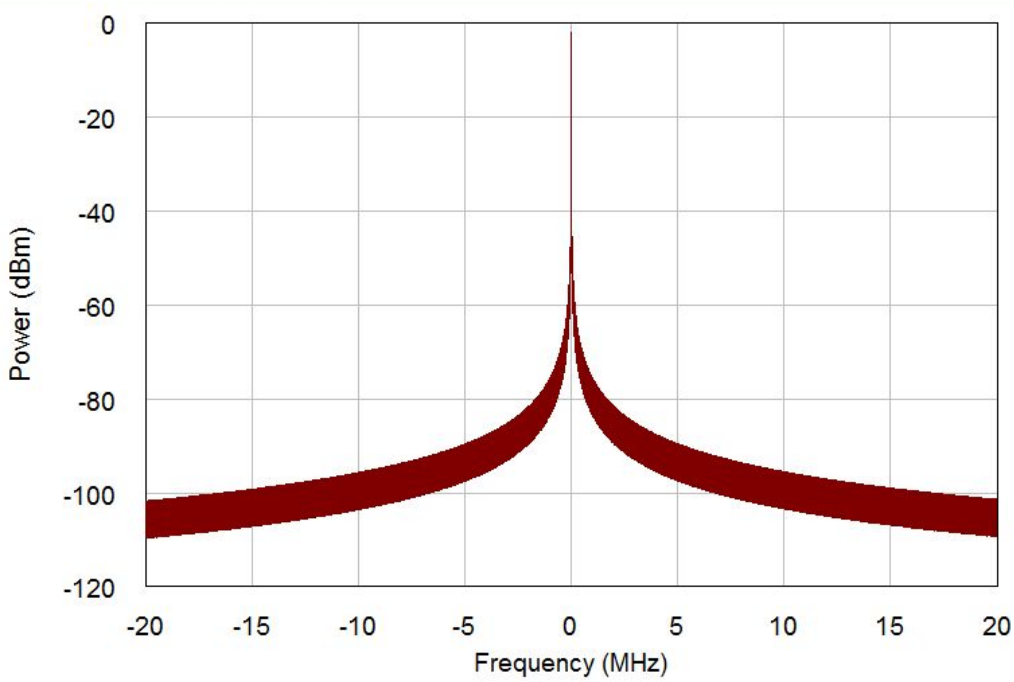


Figure 3.27. Circuit at Vcc mixer input [11]

This circuit is necessary to isolate the DC voltage from the RF power that is hold in the mixer from LO, RF and IF ports. So there is no transfer of power from one port to another.
So, from this port the mixer is fed with voltage source that can make it work and that will cause minimum distortion at the output port, IF.

Going back to the mixer itself, the purpose of this mixer is to perform a downconversion in the frequency of the signal in order to make it fit in the band from 0 to 20Khz.
For a received signal with no delay, the sustraction computed between the LO sample and the RF received signal, will produce a tone in a frequency equal to 0 Ghz. This result can be seen in Graph 3.9 and it will explained carefully in the 5th chapter of this study.



Graph 3.9. .Power at the output port of the mixer.

4.3.2. Protoshield design of the mixer.

According to manufacturer specifications, it is important to implement the application circuit of this mixer in order to obtain its best performance. The circuit that should be constructed in order to test it in a laboratory is the one shown in Figure 3.28.

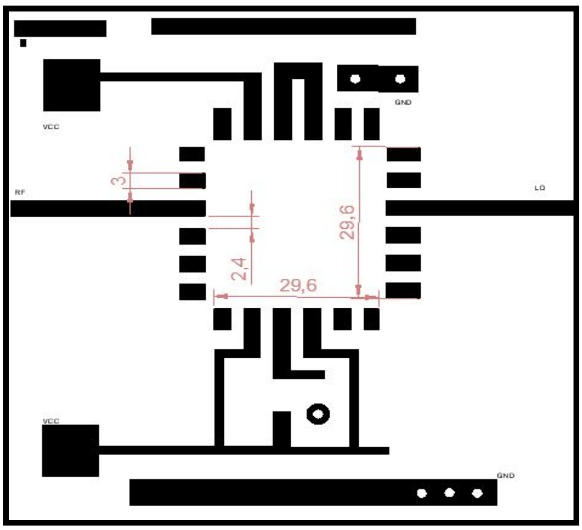


Figure 3.28. Autocad design of the mixer

5. Directional coupler

5.1. Behaviour and main parameters of the coupler.

An hybrid coupler like the one used for this system is a component that divides the power coming from the input port into the two output ports (transmitted port and coupled port) being cero the transfer of power between isolated port and input port.

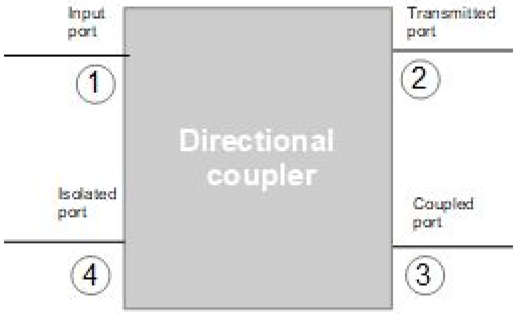


Figure 3.29. Port distribution in a directional coupler.

The output power should be equal in transmitted and coupled port. For a symmetric branch line the power at the input port will be divided like it is shown in Formula 3.15.

$$S_1 = \frac{1}{\sqrt{(2)}} \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} = \frac{1}{\sqrt{(2)}} \begin{bmatrix} 0 & j & 1 & 0 \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ 0 & 1 & j & 0 \end{bmatrix}$$

$$\begin{aligned} S_{21} = S_{12} = \frac{b_2}{a_1} &= \frac{j}{\sqrt{(2)}} \Rightarrow b_2 = a_1 \frac{j}{\sqrt{(2)}} \\ S_{43} = S_{34} = \frac{b_4}{a_3} &= \frac{j}{\sqrt{(2)}} \Rightarrow b_4 = a_3 \frac{j}{\sqrt{(2)}} \\ S_{31} = S_{13} = \frac{b_3}{a_1} &= \frac{1}{\sqrt{(2)}} \Rightarrow b_3 = \frac{a_1}{\sqrt{(2)}} \\ S_{42} = S_{24} = \frac{b_4}{a_2} &= \frac{1}{\sqrt{(2)}} \Rightarrow b_4 = \frac{a_2}{\sqrt{(2)}} \end{aligned} \qquad (3.15)$$

So it's easy to see that for an hybrid coupler, the constants α and β that characterize the coupler and its transmission between ports are both equal to 1/sqrt(2).

Ahe hybrid has a 90º phase shift between the coupled and transmitted port when the power comes from the port 1.

5.1.1. Coupling

Coupling indicates the of the input power that is coupled to the output port.

$$C=10\log\left(\frac{P_1}{P_3}\right)=-20\log(\beta)\ [dB] \tag{3.16}$$

5.1.2. Directivity

Directivity is the measure of the coupler ability to isolate forward and backward waves.

$$D=10\log\left(\frac{P_3}{P_4}\right)=-20\log\left(\frac{\beta}{|S_{14}|}\right)\ [dB] \tag{3.17}$$

5.1.3. Isolation

Isolation is the measure of the power delivered to the uncoupled port.

$$I=10\log\left(\frac{P_1}{P_4}\right)=-20\log(|S_{14}|)\ [dB] \tag{3.18}$$

It can be related to the quantities defined before like :

$$I=D+C\quad [dB] \tag{3.19}$$

5.1.4. Insertion loss

The insertion loss account for the input power delivered to the through port, diminished by power delivered to the coupled and isolated ports.

$$L=10\log\left(\frac{P_1}{P_2}\right)=-20\log(|S_{12}|)\ [dB] \tag{3.20}$$

5.2. The directional coupler of the radar system.

The coupler with the described characteristics will be constructed using microstrip lines, so it’s necessary to calculate the width and length of the lines.
The length of the transmission line will be equal to lambda/4. So for a frequency equal to 2432 Mhz, the quarter of wavelength is close to 14.2 mm.

Here is shown the calculation of the impedances or admittances that characterize symmetric coupler transmission lines.

$$Y_1 = \sqrt{(2)}\,Y_0 \Rightarrow Z_1 = \frac{Z_0}{\sqrt{(2)}} = \frac{50}{\sqrt{(2)}} = 35{,}35\,ohms$$

$$Y_2 = Y_0 \Rightarrow Z_2 = Z_0 = 50\,ohms$$

This calculations allow to figure out the value for the width and length of the lines that will be part of the directional coupler. Considering that it’s symmetric, the length and width of the horizontal lines are equal, and also are the vertical lines.

	1	2
Y	35.35 ohm	50 ohm
W	5 mm	2.91 mm
L	16 mm	16 mm

Chart 3.6. Dimensions of transmission lines in a hybrid directional coupler.

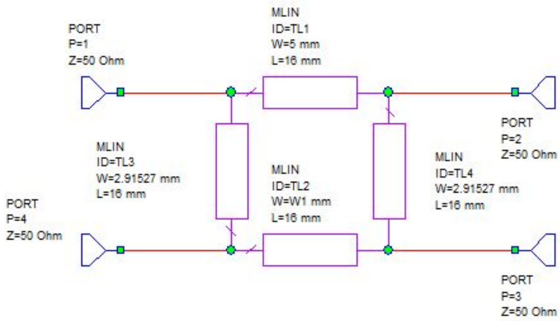
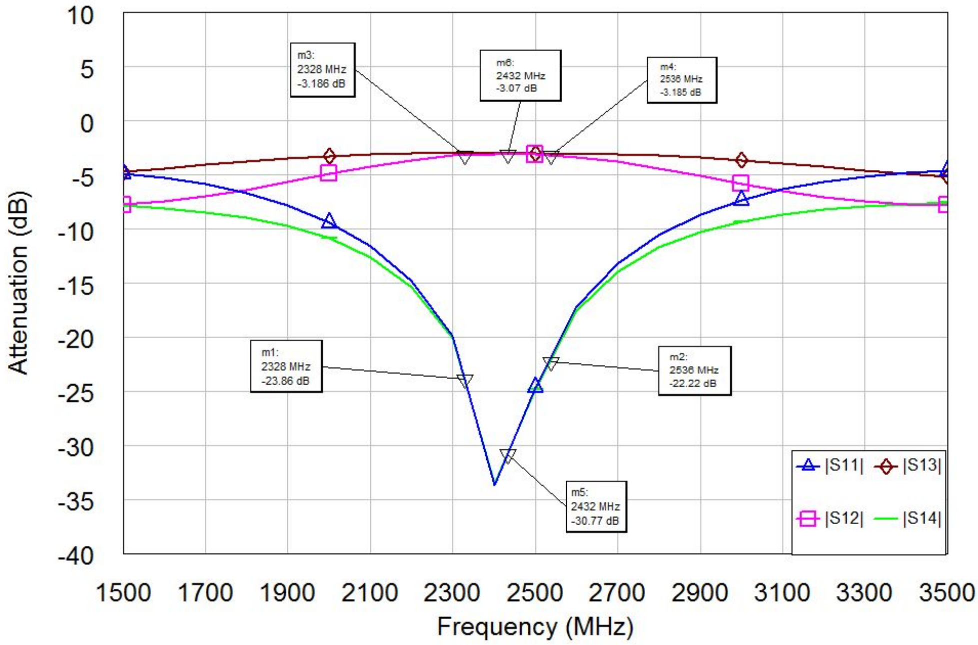


Figure 3.30. Scheme of directional coupler.

5.3. Test of the component.

5.3.1. Simulation of the component using AWR.

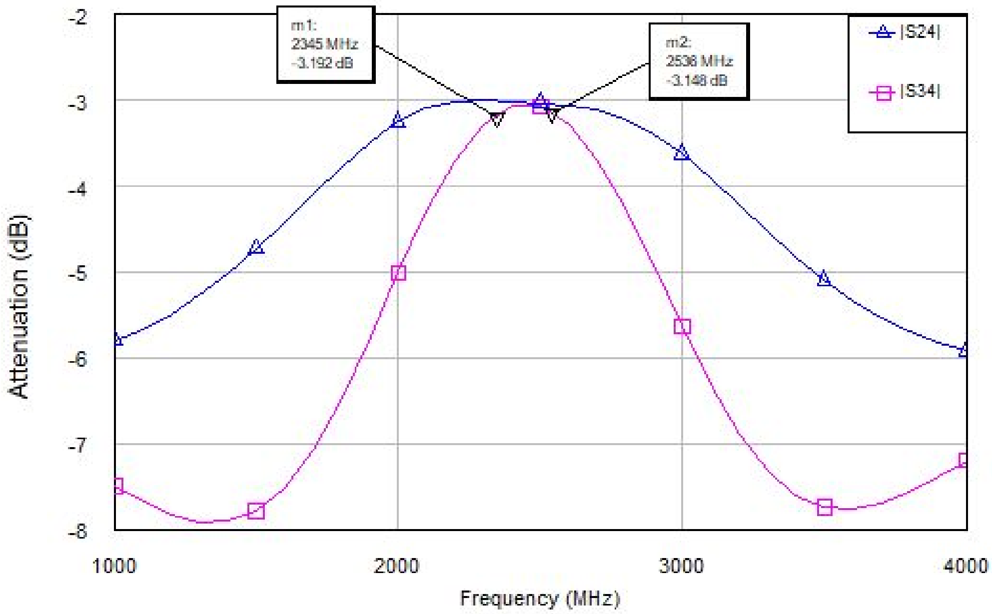
The Graph 3.10 shows the isolation between the input port and the isolated port. In the radar system, our bandwidth has an attenuation under -20dB, the transmission between the port 1 and ports 2 and 3 is -3dB that corresponds with the equal division of the input power.



Graph 3.10.. S parameters of the directional coupler design.

As shown in Graph 3.10, the coupling factor of the hybrid will be close to -3dB and so will be the insertion losses. However the isolation between ports 4 and 1, that corresponds to isolation factor and according to formula 3.20 to the parameters S14 of this network is equal to -30 dB for the central frequency of transmission of this filter.

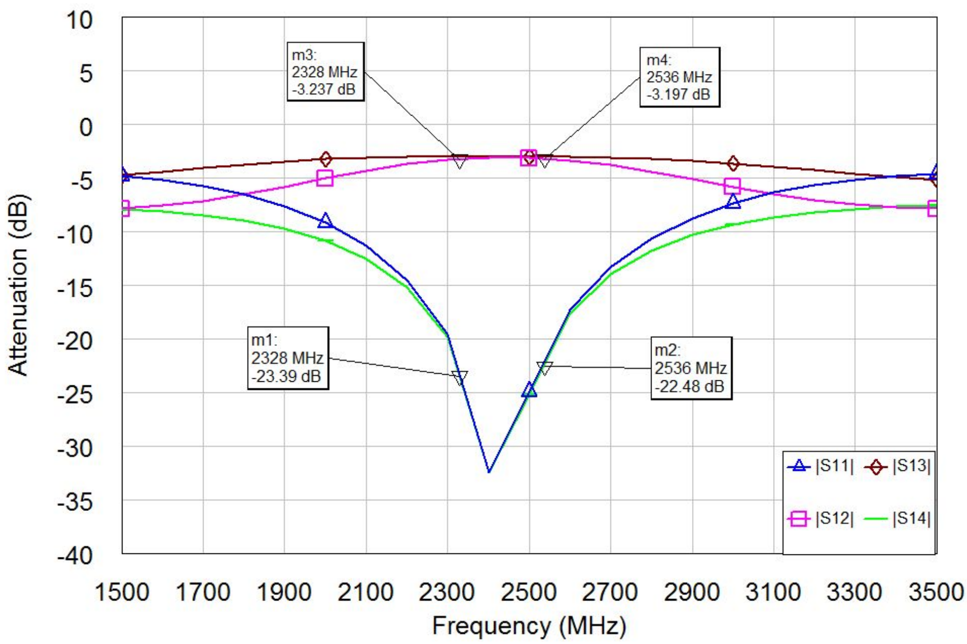
It's also important to analyse the power coming from the ports 2 and 3 to the 4 port. Because this is the signal it's going to be analyse in the receiver block.



Graph 3.11. S parameters for transmission between antennas and receiver block.

The graph above shows that the contribution of both inputs to the output 4 port is equal. Afterwards, the analysis of losses determines if there is some attenuation in the power coming to the receiver block or from the emitter block.
Graph 3.10 shows the hybrid coupler behaviour when constructed with the exact measurements that were calculated using formulas of this study.

Due to the importance on the variations of measurements in the transmission lines, Graph 3.12 shows the maximum inexactitude of measurements while constructing that could be around +-50um.. This factor affects to length, width and separation of transmission lines.
Simulation shows that the value are quite similar to the ones obtained in the simulation of the hybrid implemented with calculated values.



Graph 3.12. S parameters for design with +-50um accuracy.

5.3.2. Protoshield design of the component.

In order to be able to test it, we will need to design the model that will be implemented in the protoshield. Using this model, the real behaviour of this component could be seen by using spectrum analyser or oscilloscope.

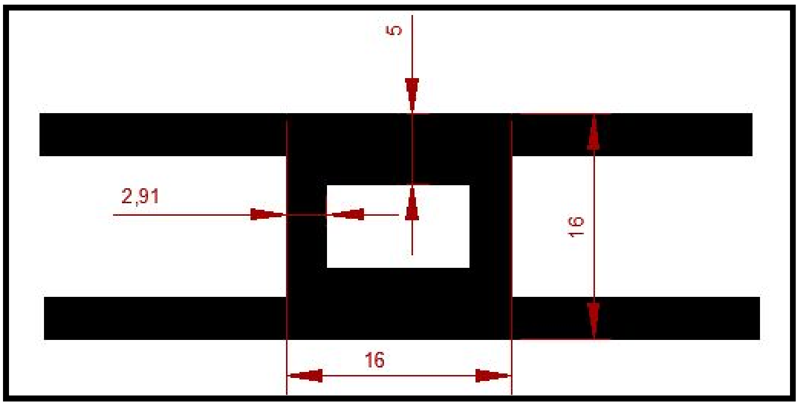


Figure 3.31. Autocad design for the directional coupler.

As illustrated in Figure 3.31, there are 4 ports that will be connected to the receiver block, transmitter port and both antennas.

6. Splitter

The splitted of the signal will be made using a coupler in order to divide the power into the one that will stay in the transmitter block and the sample that will go the mixer in the receiver block.

6.1. The splitter of the system.

According to the manufacturer, we will need -3 to 3dBm power at the local oscillator input. So, we will need to make sure that at least -3dBm reach the mixer.

For this purpose, we will use a coupler that will divide the input power in two different ports. Some of the main parameters to characterize the coupler will be the coupling, the isolation, the directivity, coupling and insert losses and work frequency.
The coupling will be calculated using Formula 3.16. The value obtained for the coupling will be equal to -18.8dB.

After that, it will be necessary to calculate the width and the separation of the coupled line that will work as a coupler and divide the frequency.

$$Z_{0o} = Z_0 \cdot \sqrt{\frac{(1-C)}{(1+C)}} = 50 \cdot \sqrt{\frac{(1-0.2)}{(1+0.2)}} = 40.82 \ ohms$$

$$Z_{0e} = Z_0 \cdot \sqrt{\frac{(1+C)}{(1-C)}} = 50 \cdot \sqrt{\frac{(1+0.2)}{(1-0.2)}} = 61{,}23 \ ohms$$

Now, it is necessary to simulate this impedances in order to know the width and the separation between the lines in the coupler.
The separation between lines is bigger than the ones seeing before, the main reason is that the coupling between the lines is quite soft due to the low power level needed at the LO sample port.
The final measurements obtained for the transmission lines in this coupler can be seen in Figure 3.32

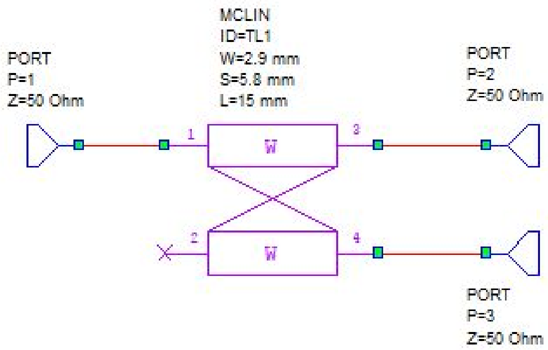
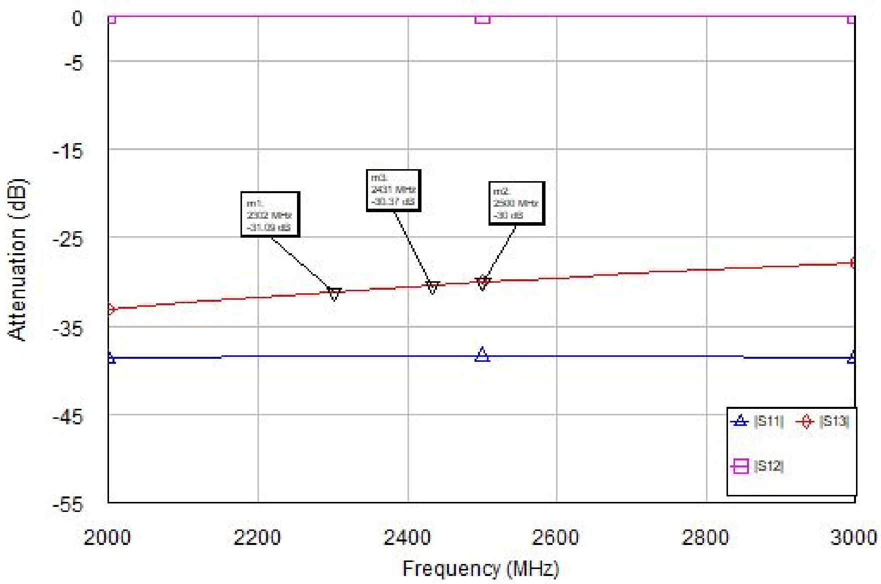


Figure 3.32. Circuit scheme of the splitter.

6.1.1. Test of the component.

6.1.1.1. Simulation of the component using AWR.

According to the calculations made in previous pages, the splitter constructed is composed by a coupled transmission line with the same width as the input transmission line.



Graph 3.13. S parameters of the splitter.

The sample give to the mixer through the local oscillator port will have levels between -30 and -29 dB, which is equivalent to the 0 dBm specify by the manufacturer of the mixer ad typical value for the input.

6.1.1.2. Protoshield design of the component

For the test of the component in the laboratory, it will be necessary to implement this component in a protoshield.

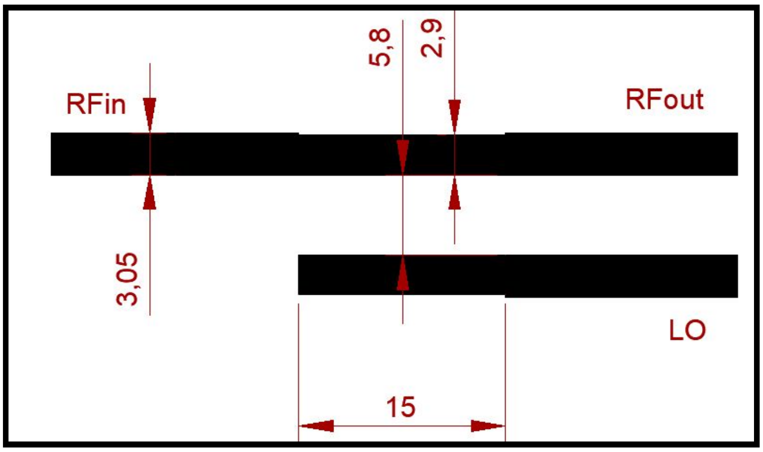


Figure 3.33.Autocad design of the splitter.

7. Antenna

An antenna is a device that converts guided electromagnetic wave and a transmission line into a plane wave that propagates in free space. Since antenna is a bidirectional device, it can either receive or emit these plane waves. The quality and the amount of power received will depend on the parameters of the antenna.

7.1. Behaviour and main parameters of antenna.

7.1.1. 3dB beamwidth

One important measurement is the ability of the antenna to focus in a certain direction of propagation. It can be measured by using the 3db beamwidth of the signal propagated as shown in Figure 3.34.

The 3dB beamwidth is defined as the angular width of the main beam as which the power level has dropped 3 dB from its maximum value.

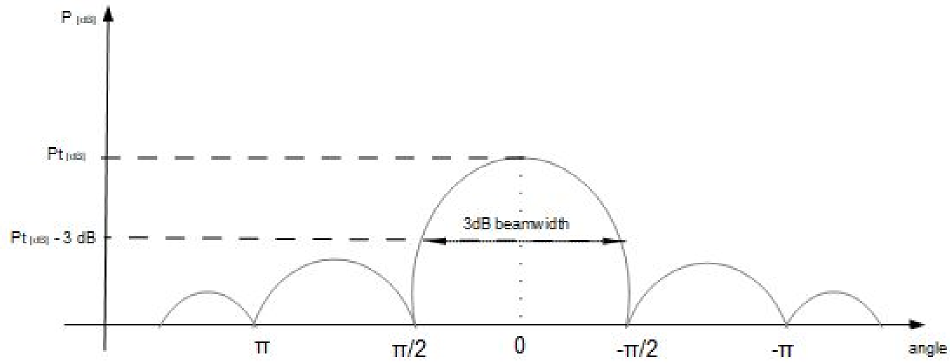


Figure 3.34. Radiation pattern of an antenna.

7.1.2. Directivity.

Directivity is the radio of maximum radiation intensity in the main bean to the average radiation intensity all over space.
An antenna that radiates the same amount of power in all surrounding space is called isotropic. The directivity of this antenna is equal to 1.
The directivity of any antenna will be related to the directivity of isotropic one and written as dBi units.

The directivity is related with the 3dB beamwidth using the measurements of the main lobes.

$$D \approx \frac{32400}{\theta_1 \theta_2} \tag{3.21}$$

7.1.3. Gain

The gain of the antenna is the difference between transmitted power in the main lobe between an isotropic antenna and the antenna that's been measured.

To make the antenna more precise once the target is been located, the gain should be as big as possible. If the antenna of the radar is trying to track de target, it's necessary to radiate in all directions so we can receive echo from different positions in space.

$$G = \eta_{rad} \cdot D \tag{3.22}$$

7.1.4. Effective isotropic radiated power (EIRP)

EIRP measures the amount of power radiated at the antenna in a given direction and compares it with the amount of power a perfectly isotropic antenna would need to radiate to achieve the measured value.

$$EIRP\ [dB] = P_t - L + G \tag{3.22}$$

7.1.5. Effective aperture.

The aperture of an antenna is defined as the area where radiation occurs. The aperture efficiency of the antenna is defined as the ratio of the actual directivity related with the maximum directivity given by Formula 3.23.

$$D_{max} = \frac{4\pi\ A}{\lambda^2} \rightarrow D = \eta_{ap} \frac{4\pi\ A}{\lambda^2} \tag{3.23}$$

The effective aperture area can be interpreted as the “capture area” of a receive antenna.

$$A_e = \frac{D\ \lambda^2}{4\pi} \tag{3.24}$$

7.1.6. Far-field.

Region where the radiated wave from the antenna takes the form of a plane wave. This distance is determined by the maximum dimension of the antenna and the wavelength of the radiated wave as

$$R_{ff} = 2D^2 / \lambda \qquad (3.\ 25)$$

The radiation patterns of antennas should be analysed in this region.

7.2. Antenna for our system. Vivaldi antenna.

7.2.1. Vivaldi antenna.[2]

The vivaldi antenna is a tapered slot antenna with planar design that work over a wide frequency range. It can be made using a doubled-laminated PCB material, a piece of sheet metal or a dielectric plate metalized.

The feeding line excites the open space in the antenna by a microstrip line (unbalanced line) connected to a coaxial cable (balanced line). This adaptation is made using a balun that transforms unbalanced systems into balanced ones.
A balun forces an unbalanced transmission line to properly feed a balanced component. This could be made by forcing the current to be zero by implementing an open circuit.

The propagated wave will depend on the shape of the antenna. The upper frequency of propagation limited by the width of the gap, while the lower frequency by the size of the opening.

The shape of the antenna is the following :

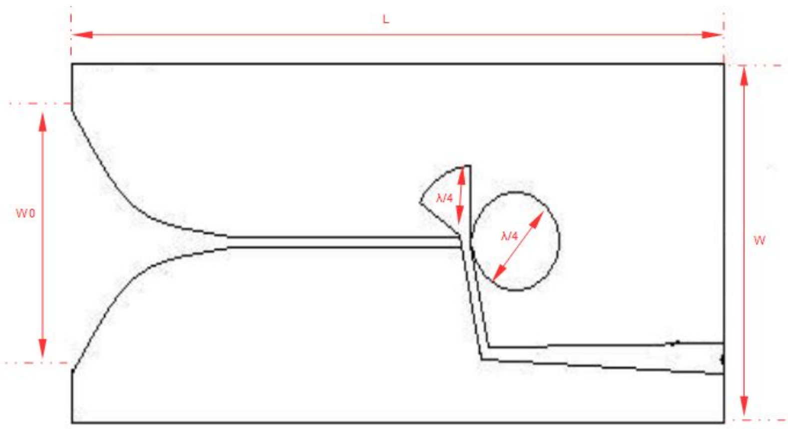


Figure 3.35. Scheme of the Vivaldi antenna.

All the measurements will be calculated depending on the frequencies of the transmitted signal. λ_{min} and λ_{max} are the equivalent wavelengths of the minimum and maximum frequencies in the bandwidth.

- Length of the antenna.

$$L > \frac{\lambda_{min} + \lambda_{max}}{2} \tag{3.26}$$

- Width of the antenna.

$$W > \frac{\lambda_{min} + \lambda_{max}}{4} \qquad (3.27)$$

- Mouth opening of the antenna, where f_{min} : minimum frequency of transmission ; ε : permittivity of dielectric FR4.

$$\lambda_g = \frac{c}{f_{min} \cdot \sqrt{(\varepsilon)}} \qquad (3.28)$$

$$W_{max} > W_0 > W_{min} \quad \rightarrow \quad \frac{\lambda_g}{2} > W_0 > \frac{\lambda_g}{f\,\varepsilon} \qquad (3.29)$$

For these measurements, the antenna radiates at the frequencies inside the bandwidth of the system and it maximize the directivity of the antenna.
The main goal is to achieve the match at the input antenna so the return losses of the antenna are minima. That meaning the maximum amount of power coming to the antenna is radiated and almost none is lost in the from the input to the output of the antenna.

7.2.2. Design of the antenna.

For the design of the Vivaldi antenna, it is necessary to calculate some measurements. According to the resource [2] and the procedure shown on it.
The measurements of the antenna are listed below.

· Length of the antenna : L > 123.5 mm → *L = 130 mm*
· Width of the antenna : W > 61.75 mm → *W = 70 mm*
· Mouth opening of the antenna : 29.75 mm > W0 > 27 mm → *W0 = 28 mm*

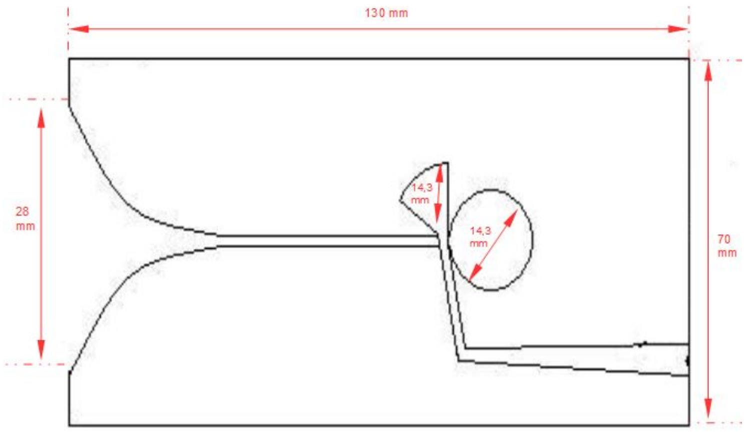


Figure 3.36 . Measurements of the Vivaldi antenna of the system.

7.2.3. Array of Vivaldi antennas.

In some applications, it is necessary to increase the directivity of the antennas used for the design. For this reason, more than one antenna could be used for the same purpose generating an array of antennas. The radiation diagram obtained will be the sum of the radiation of each antenna and their interferences between one another.

In the system, both antennas will be placed in the same axis and they will be provided the same amplitude but a difference in phase equal to π/2. This difference in phase is caused by the transmission and coupling at the ports in the hybrid coupler.
In their normal axis, the radiation of the antennas will be constructive whether in the direction of the axis they're placed in, the radiation will be destructive.

Assuming that one of the antennas is place in the center of coordinates and the other one is separate a distance d from it, the radiation vector of the two antenna can be described as shown in Figure 3.38.

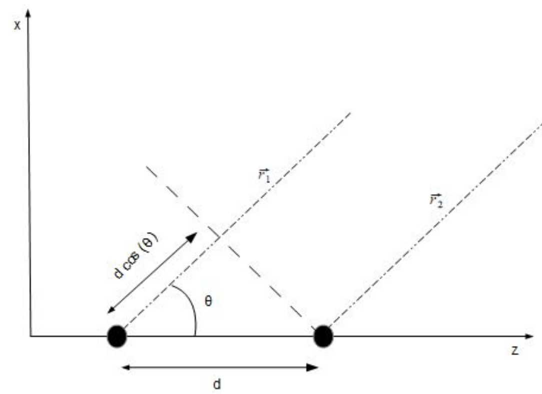


Figure 3.37. Array disposition and interferences.

$$\vec{N} = \vec{N}_0 \left(1 + e^{jk\hat{r}\cdot\vec{r}_1}\right) \tag{3.30}$$

being No the radiation vector of the antenna and the origin of coordinates.

The electric angle for the array can be defined as the difference in phase and in paths of propagations of the two antennas. Being d the distance that separates them and **α** the difference in phase.

$$\Psi_z = k_z d \cos(\theta) + \alpha \tag{3.31}$$

$$\Psi_z = k_z d \cos(\theta) + \alpha = \frac{2\pi}{\lambda} 1.057 \lambda \cos(\theta) + \frac{\pi}{2}$$

Using this expression, it is possible to calculate the Array factor of the antenna array, FA, that will be calculated using expression.

$$FA(\Psi) = \sum_{n=1}^{N-n} a_i e^{j\Psi} \tag{3.32}$$

For two antennas of equal amplitude, a difference in phase equal to **π**/2 and a distance between them close to 0.2ƛ the array factor will correspond to the formula FA = $a_i + a_i\, e^{j(kd\cos(\Theta) + \alpha)}$, a variation from Formula 3.32. For theta equal 0º, the value of the array factor will be 13.0713.

Due difference in phase between the two radiated waves and the separation between the antennas, one of the lobes in the radiation diagram is placed between the antennas and some other grating lobes may appear if we increase the distance to a value higher than ƛ/2. However the directivity is higher and that increases the level of radiated power.

The directivity and the solid angle due to the interference between antennas in the array. Using formulas, it will be possible to calculate them.

$$\Omega = \frac{4\pi}{N} + \frac{4\pi}{N^2} \sum_{n=1}^{N-1} \frac{(N-n)}{nkd} 2\cos(n\alpha) sen(nkd) \tag{3.33}$$

$$D = \frac{4\pi}{\Omega} = \frac{1}{\frac{1}{N} + \frac{2}{N} \sum_{n=1}^{N-1} \frac{(N-n)}{nkd} 2\cos(n\alpha) sen(nkd)} \tag{3.34}$$

The value obtained for the solid angle of the antenna after the calculation is $\Omega = 2\pi + \frac{1}{2}$, whether the value of the directivity for the array is $D = 4\pi / 2\pi + \frac{1}{2} = 1.85$. That means that the directivity of the antenna will increase by a factor of 1.85.

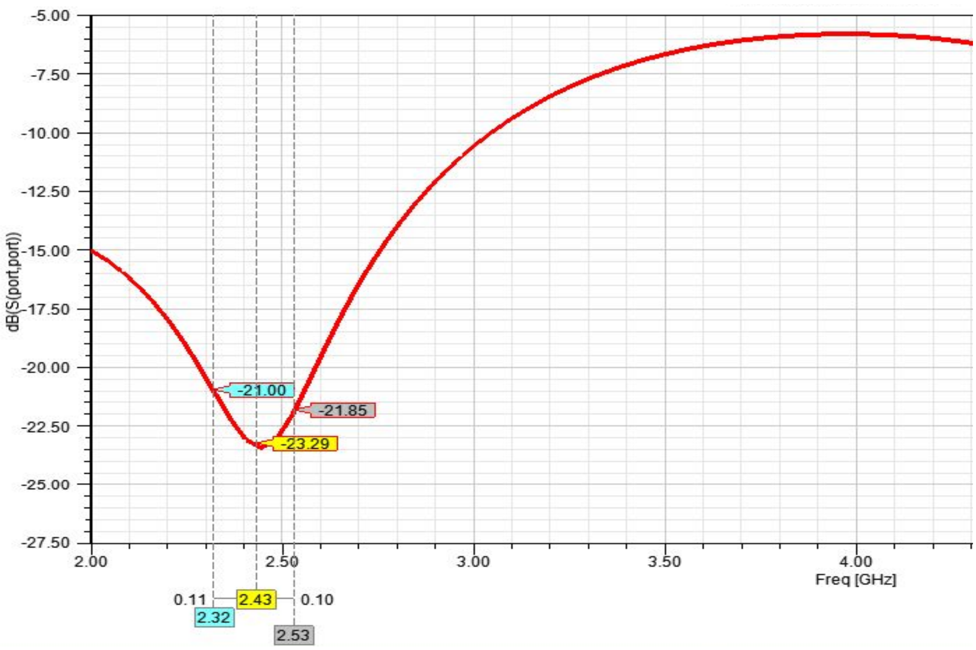
7.3. Test of the antenna

7.3.1. Simulation of the antenna using HFSS studio.

The antenna is simulated using Ansys HFSS. This program allow us to simulate the radiation, calculate the gain, return losses or SWR of the antenna designed.

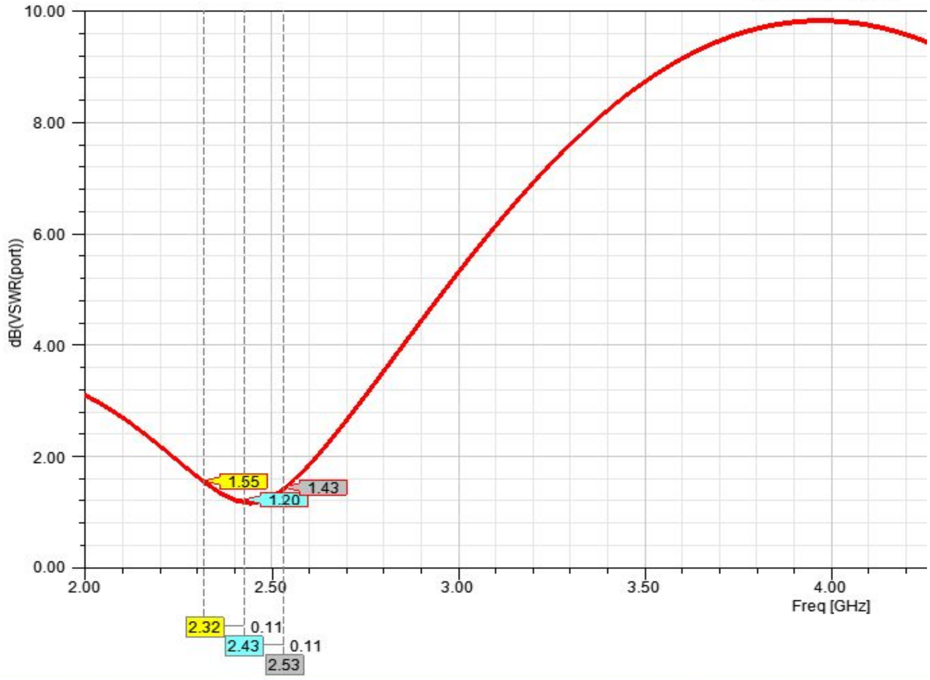
In Figure 3.36 are shown the layer of dielectric FR4 and over it an alumina patch. For the feeding of the antenna, a microstrip line is used and converted in a coaxial line, a balanced line. [2]

The return losses of the antenna, shown by the representation of the transmission parameter S11 in Graph 3.14, will be lower than -21 dB, that is equivalent to -51 dBm. Considering that the system is transmitting 18 dBm approximately, the amount of power reflected from the antenna is suitable for this design.



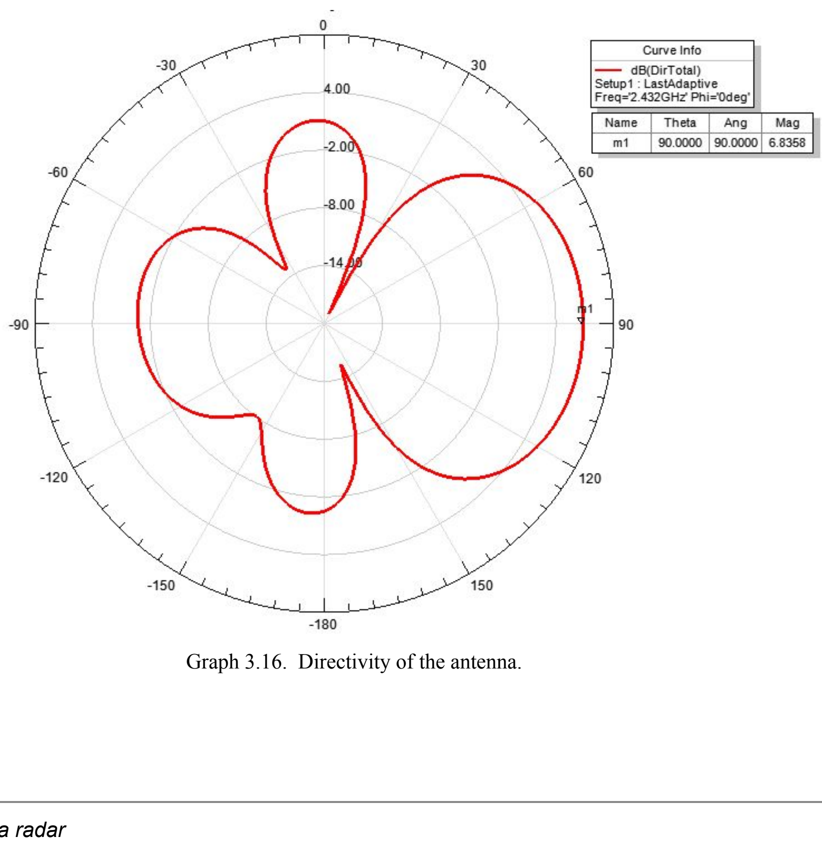
Graph 3.14. Return losses of the antenna.

It is important to determine the standard wave ratio (SWR) level for the antenna. This measurement determines the impedance matching of the antenna load and the characteristic impedance of the transmission line connected to it. For all transmission lines designed for the radar system the characteristic impedance is 50 ohms.



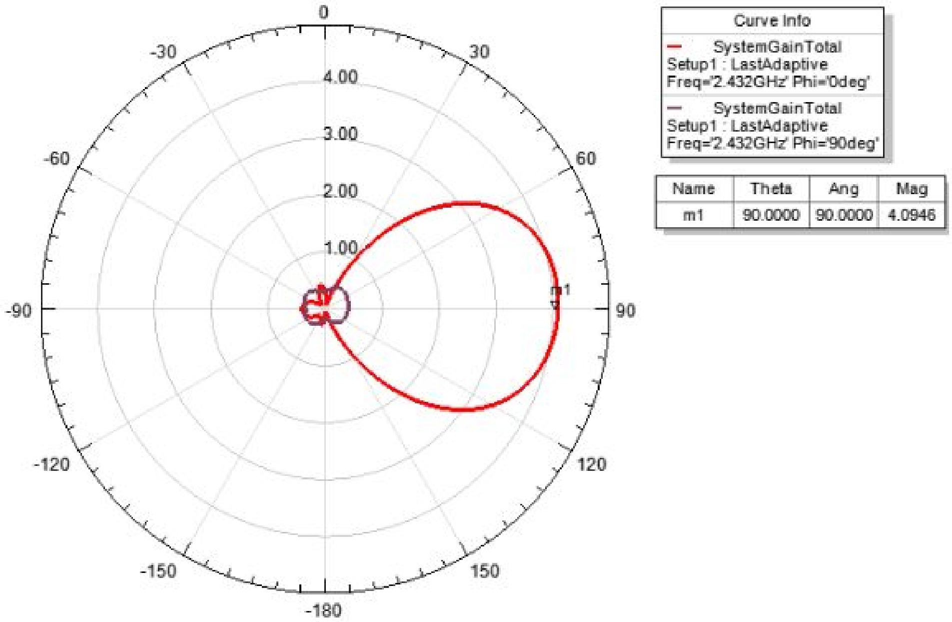
Graph 3.15 . SWR of the antenna.

In order to determine the efficiency of the design and the amount of power radiated, the measurements needed are the directivity and the gain of the antennas.
The peak value situated at Θ= 90º, will measure the directivity of the antenna. In this radiation plot, this value is equal to 6.8 dBi.



Graph 3.16. Directivity of the antenna.

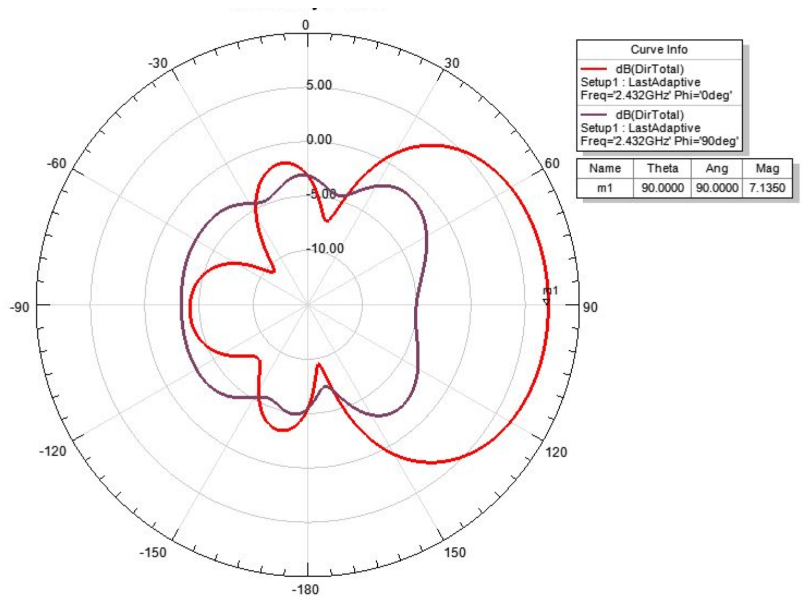
Regarding the gain of the antenna, the value situated in Tetha = 90º, will be G = 4.0946 dB.



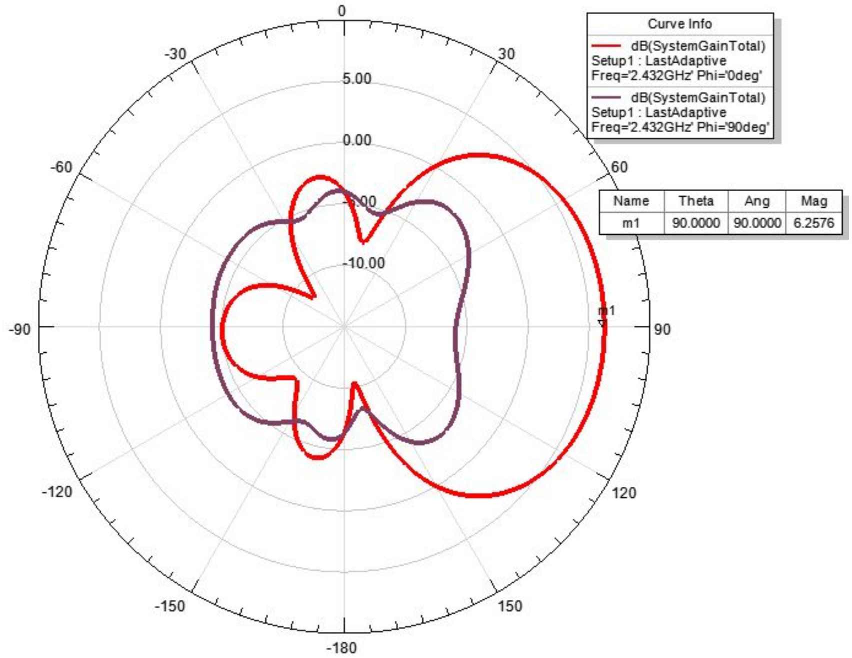
Graph 3.17. Gain of the antenna.

7.3.2. Simulation of the array using HFSS studio.

The array of antennas used for this implementation modifies the parameters of the antenna, and for that reason also the value of power radiated.
The directivity of the array is modified along with the gain. After simulation, it is possible to see that both values have been increased. The final value for the directivity of the antenna is 7.13 dBi whereas the final value of the gain is 6.25 dB.



Graph 3.18. Directivity of antenna array.



Graph 3.19. Gain of antenna array.

Considering the value of both parameters and the relation between them, it is clear that the radiation efficiency had increased to a value closer to 1.

Quadrupole theory could be also applied to this scheme to evaluate the transmission of power between antenna ports. For this reciprocal quadrupole, the transmission parameters are the following.

$$S11 = 0.04\text{-}0.15j = S22$$

$$S12 = 0. +0.02J = S21$$

7.3.3. Protoshield design of the antenna.

In order to test the antenna in the laboratory it will be necessary to design a protoshield model. In Figure 4.1, it is possible to distinguish the dielectric, the patch and all measurement of the antenna.

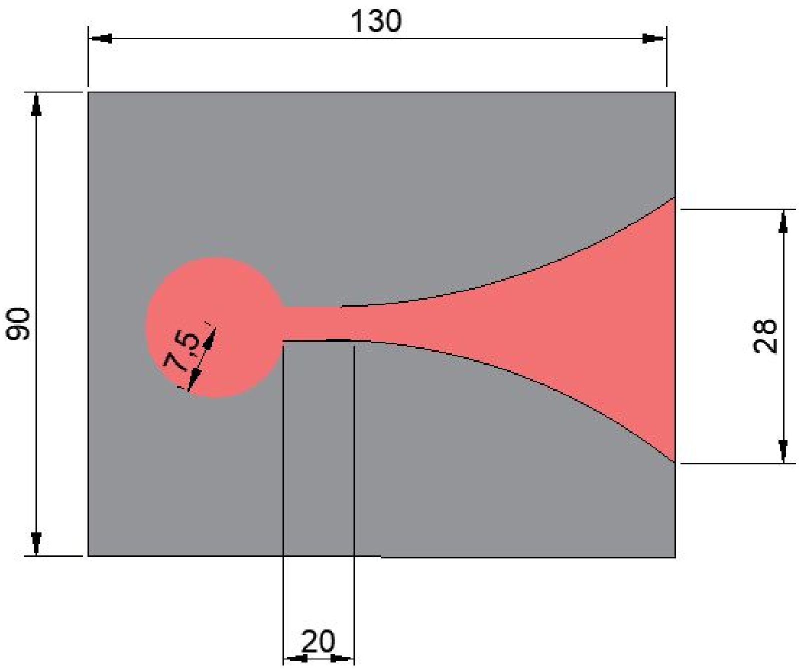


Figure 3.38. Autocad Design of the Antenna.

Chapter 4

Radar behaviour.

Analysis of simulation results.

This chapter studies all results extracted from the simulation of the system. The simulation is performed by using AWR Design Environment, as it was done in previous simulations.

At the beginning, this chapter is going to evaluate all signals in the system. It is going to study the generation of the chirp signal along with the reception of the echo and its adaptation for analysis.

After that, the radar itself is going to be characterized. Conclusions and features extracted will determine maximum range, noise at the receiver, positions of blanks in frequency or resolution of the radar designed.

1. Analysis of main signals of radar system.

As a starting point for this analysis, the following paragraphs are going to present all signals generated by the components that constitute this radar.
It is interesting to see how each parameter of the components affects to the final results obtained for the transmitted and received signals. All simulations are made for a target that generates a delay equal to 0.1 ms that will make possible to appreciate the changes and quantities.

1.1. Transmitted signal

The transmitter block is composed by 5 components. Each component introduces non linearities, losses and some other parameters that will change the spectrum of the signal generated. In the *Figure 4.2* , every parameter that introduces distortion is listed under the component that cause it.

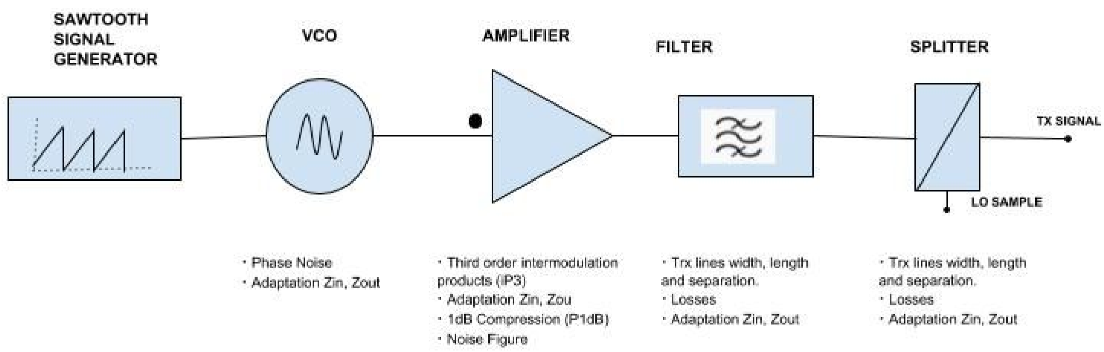
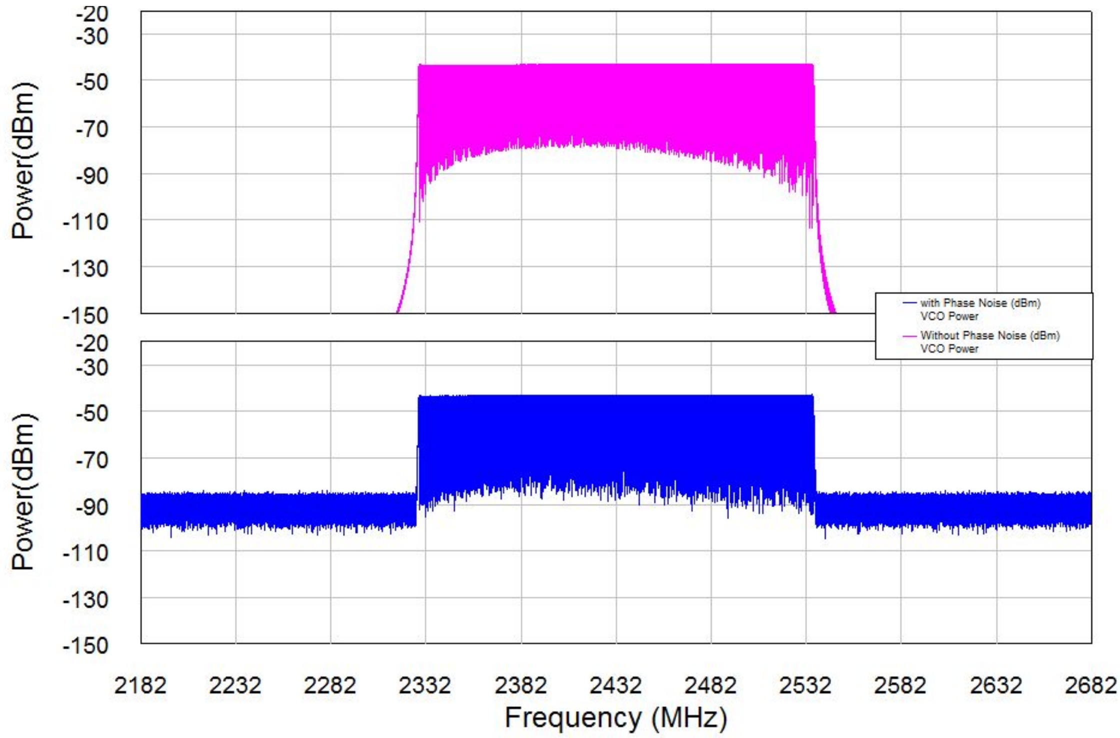


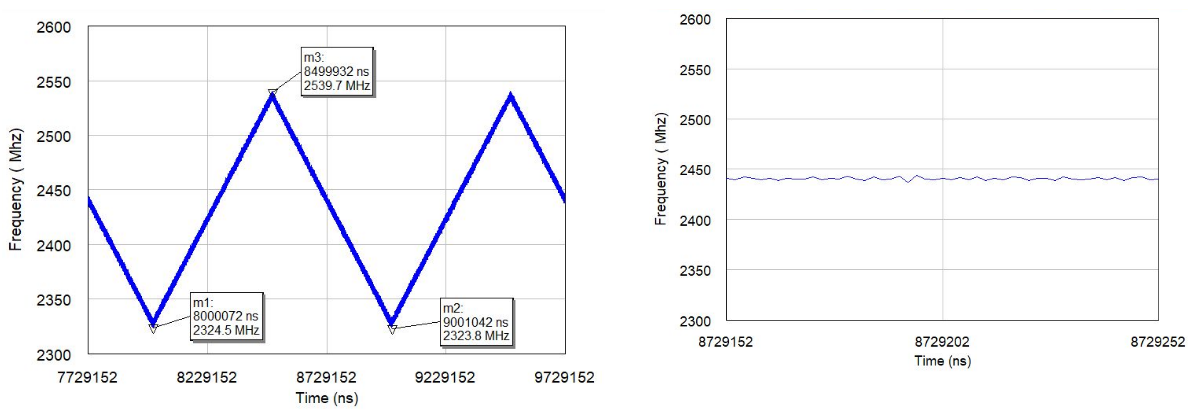
Figure 4.1. Emitter block and its parameters.

Analysing step by step, it is possible to see the changes that all these parameters produce in the chirp signal generated. The VCO introduces phase noise that changes the signal at the output by introducing noise and higher variations in the power of the spectrum as it is shown in the Graph 4.1.



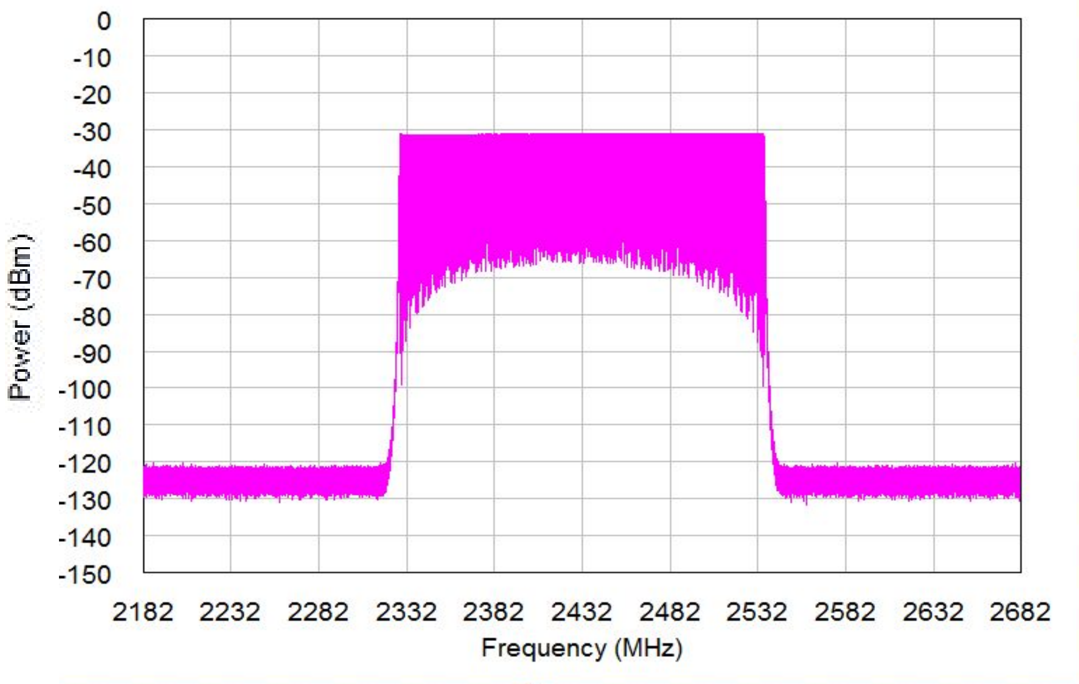
Graph 4.1. Power spectrum of VCO output signal. with and without phase noise.

The frequency of the VCO output signal doesn't change along with the introduction of phase noise in ideal. But it can be seen that the frequency variations are higher with the introduction of phase noise. The frequency is not completely stable, it has some interferences that makes the frequency variates.



Graph 4.2 VCO frequency. Effect of the phase noise and detail of this graph.

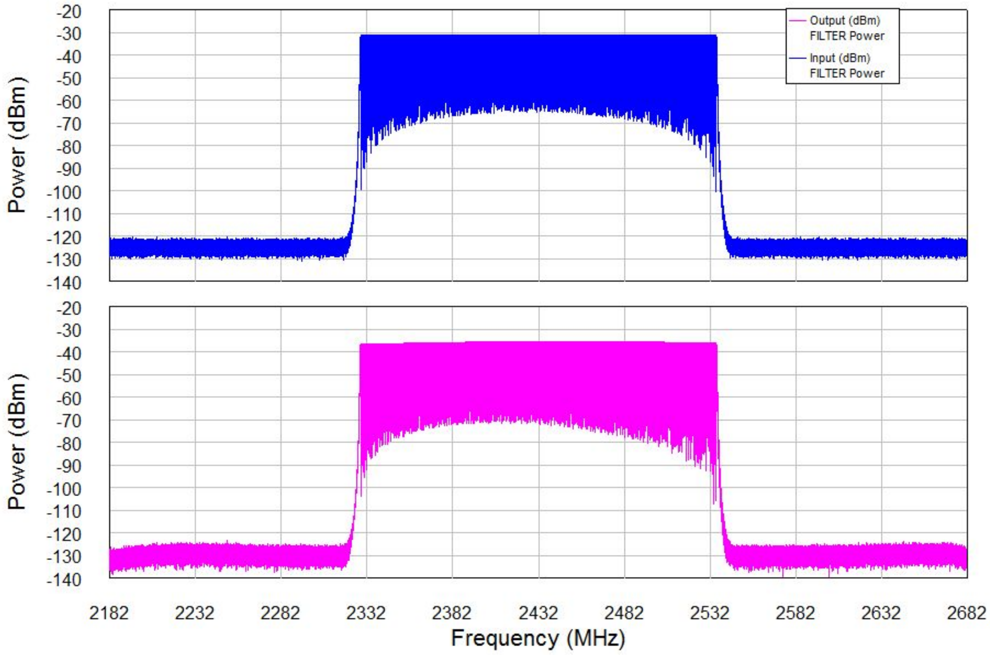
Next component of the transmitter system, the amplifier, has some parameters that could produce some lack of linearity in the gain of the amplifier when it reaches certain input power levels. According to the manufacturer, the gain expected is close to 18.5dB. However, at power levels close to 18.5 dBm, the difference between the real gain and the one expected in a linear behaviour is close to 1dB.
Intermodulation products are sources of distortion that introduce different tones in the spectrum. The emergence of these tones subtracts power from main tone of transmission, attenuating it and also introducing ghosts in the received signal.
Another parameter to take in count is he noise figure established by the manufacturer. It introduces noise in the spectrum as so does the phase noise factor in the VCO.



Graph 4.3. Power spectrum of amplifier's output signal

A different parameter that could modify the power of the spectrum is the adaptation at the ports of the amplifier. The specifications given by manufacturer were calculated for input and output impedances of 50 ohms. When these impedances are different than the ones expected the power at the output decreases due to the lack of adaptation.

The following component of the system, the bandpass filter of the transmitter block, intends to eliminate all frequencies out of our transmission bandwidth as illustrated by Graph 4.4



Graph 4.4. Filter effect in the power spectrum of the signal.

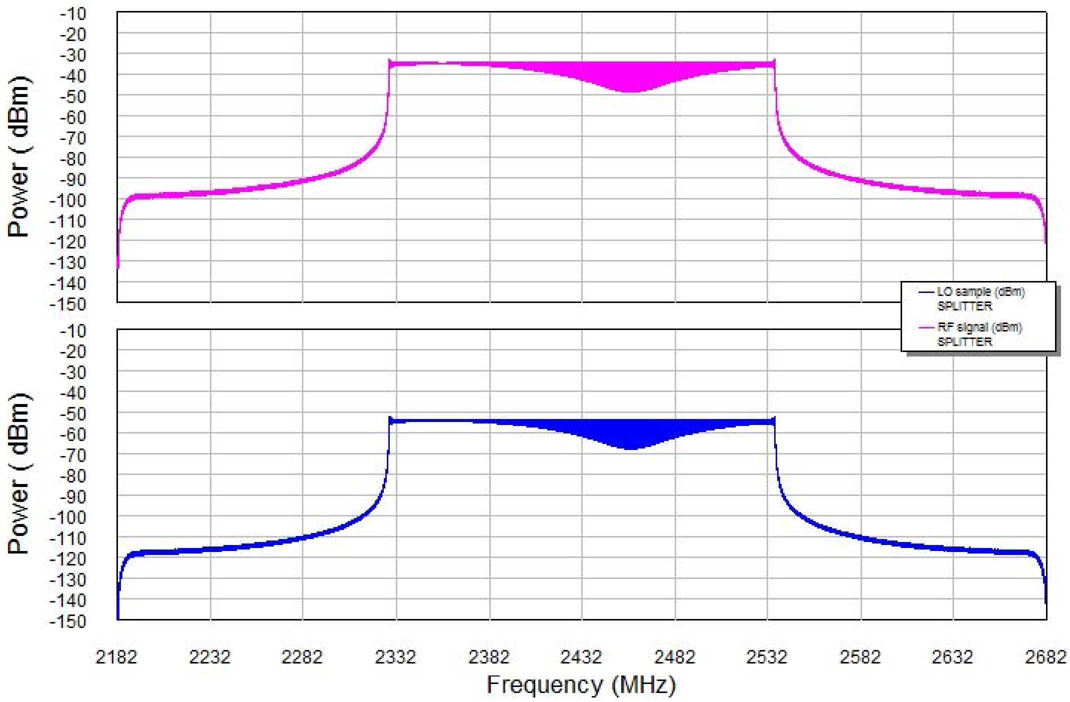
Regarding the design of the filter previously described, some factors that can cause distortion in the spectrum of the RF signal are the size of the transmission lines and the lack of adaptation at the input and output of the component.

These two parameters can increase the attenuation in all frequencies of our spectrum. It would be strongly recommendable to avoid them in order to have the best response from the filter designed.

In the construction of a coupled lines filter like the one used for this application, the accuracy of the construction is not always the most precise, so the results for this filter depends also in how close the constructed measurements are to the calculated one. In the case of the filter in the system the accuracy is +-50um. However, the low effect of this lack of accuracy in the filter mask was already shown in Chapter 3 of this text.

Last element of the transmitter block is the splitter, implemented by a coupler. The purpose of this splitter is to extract a sample from the local oscillator signal. This sample will be use at the mixer and its power needs to be close to 0 dBm according to specifications of the manufacturer.

In the graph below we can see the division of power between the transmitted RF signal and the LO sample extracted.



Graph 4.5 Power spectrum of LO sample and transmitted signal at the splitter.

The power levels at the input and output of the transmitter block are shown in Figure 4.2 . It is shown that the sample extract from the splitter will be close to 1 mW. The rest of the power at the output of the filter will be transmitted.

Along with the power levels, the central frequency and sampling frequency values are shown for each element in the system.

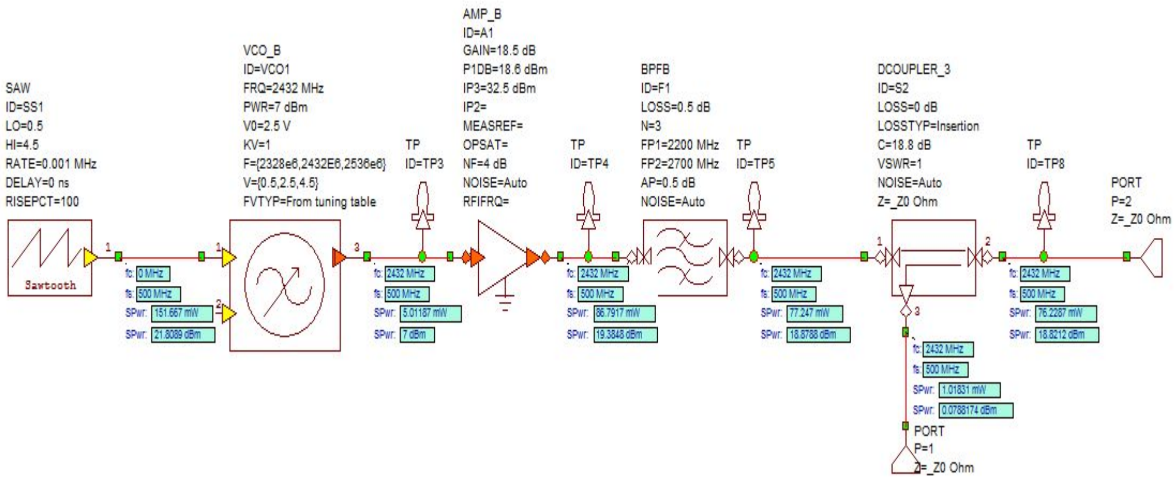
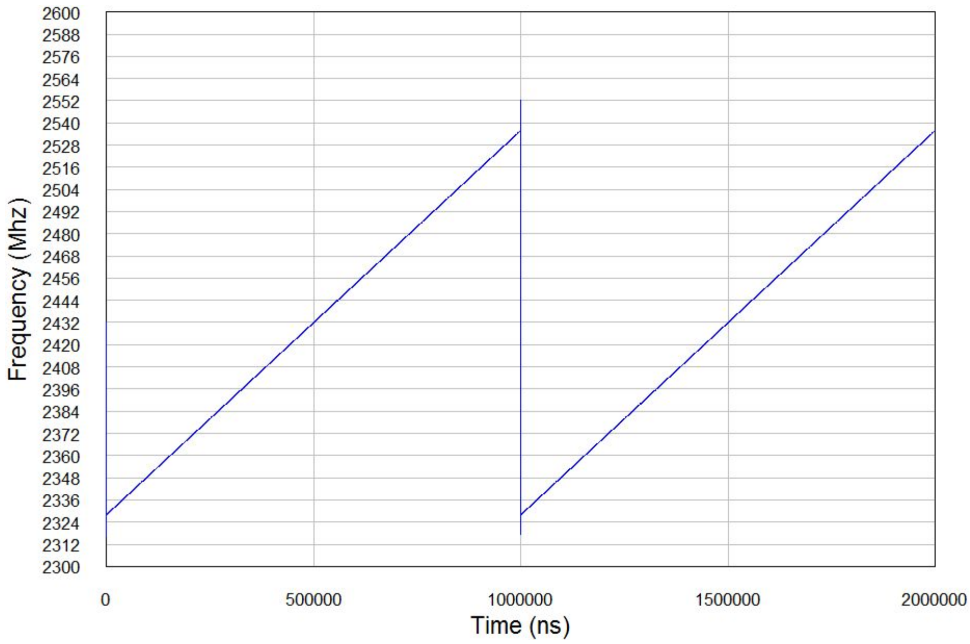


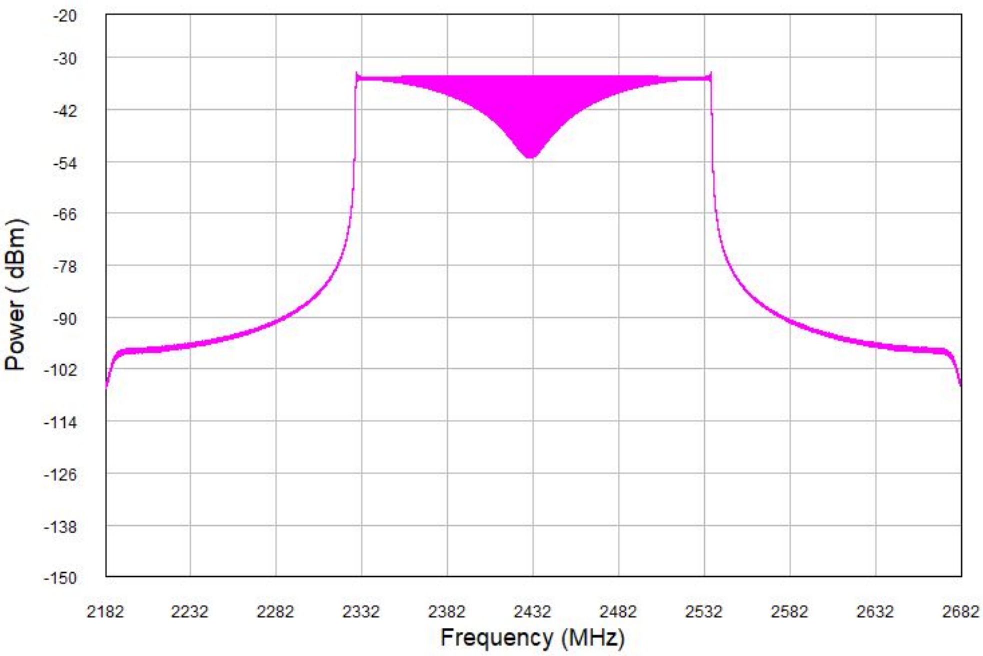
Figure 4.2. Transmitter block systems. Extracted from AWR simulation.

Main and most important values from this block are the center frequency of the signal and the power level in the spectrum. The center frequency of the signal is 2432 Mhz and the power level in this simulation is 18.8 dBm.

For comparison with the received signal at the end of this text, it is interesting to see the power spectrum, the instant frequency of the transmitted signal.



Graph 4.7. Instant frequency of transmitted signal.



Graph 4.8. Power spectrum of transmitted signal.

However, real elements include more parameters of distortion, non linearities, noise, that could change the values listed before. Real values for power transmitted or noise will be only available when simulating in laboratory.

1.2. Received signal.

The receiver block is composed, as it's been explained in previous chapters, by 4 components: a passband filter, an amplifier, a mixer and a low pass filter.
Each component introduces non linearities, losses and some other distortion parameters that will change the spectrum of the chirp signal generated.
In the *Figure 4.3* , every parameter that introduces distortion in the received signal is listed under the component that cause it.

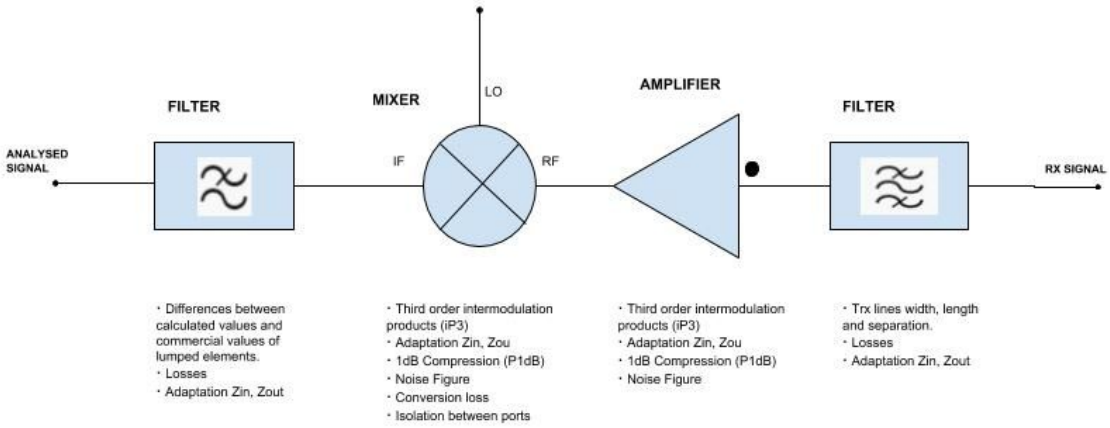


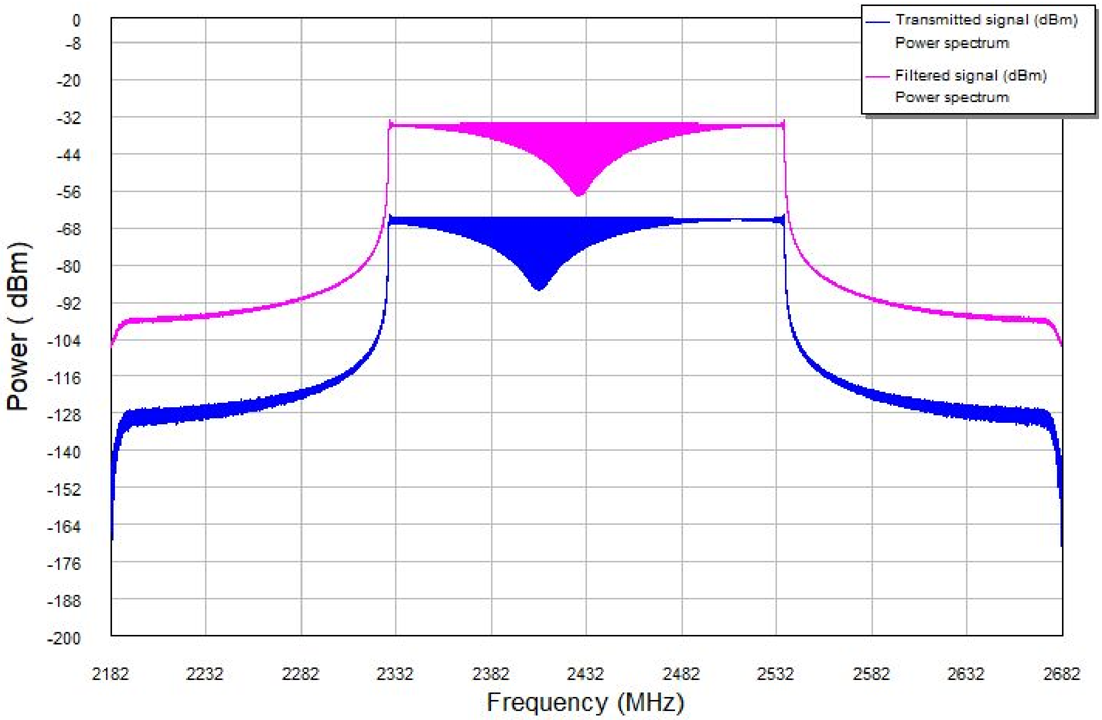
Figure 4.3. Receiver block and its parameters.

The received signal, as we have explained, has some losses in the reception of the echo and the conversion of the received wave into a signal we will be able to analyse.
For that reason, the signal that arrives to the receiver block has low power, lots of distortion and noise produced by surrounding media and antennas.
For the simulation using AWR, we will substitute the antenna with an attenuator and a RF delay that will produce the same attenuation as the equivalent impedance of the antenna. Due to the limitations of the simulator, this is the closest approach to the real system we will be able to reach.
However, real results, as we've mentioned before, will be obtained in the simulation at the laboratory.

Step by step, the received signal is going to be analysed through its element of the receiver block. This approach help us determine the influence of the parameters of distortion from each element.
As shown in Figure 4.3, the first element in this block is a bandpass filter. This filter helps us reduce noise from the received signal and it also avoids the saturation of the amplifier.
The filter attenuates all frequencies in our spectrum in bigger or smaller proportion, so we need to be aware of the attenuation that is performed in the passband of the spectrum. The technology chosen to design this filter is coupled lines design so the losses due to the design were already minimise. However, it is necessary to take in count the accuracy of construction in the protoshield that will be close to +-50 um. This fact produces some changes in the mask of the spectrum as well as in the RF signal at the output of the filter.

The effect of the minimum accuracy in the mascara of constructed filter was already shown Chapter 3 of this text.

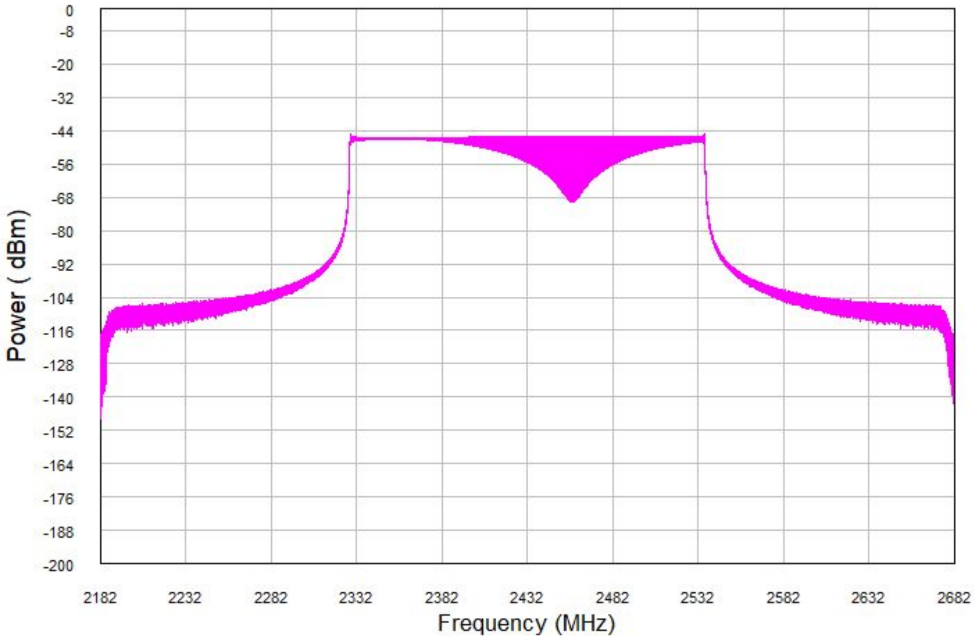
Graph 4.9. illustrates the power spectrum of the signal at the output of the passband filter in comparison with the transmitted pulse. The attenuation in the signal is the product of the attenuation of the absorbed wave and the attenuation from the filter. It is important to remember that this simulations has been performed by imposing and attenuation of 30dB in the received signal and a delay of 0.1 ms in the received pulse.



Graph 4.9. Power spectrum of filtered signal and transmitted signal.

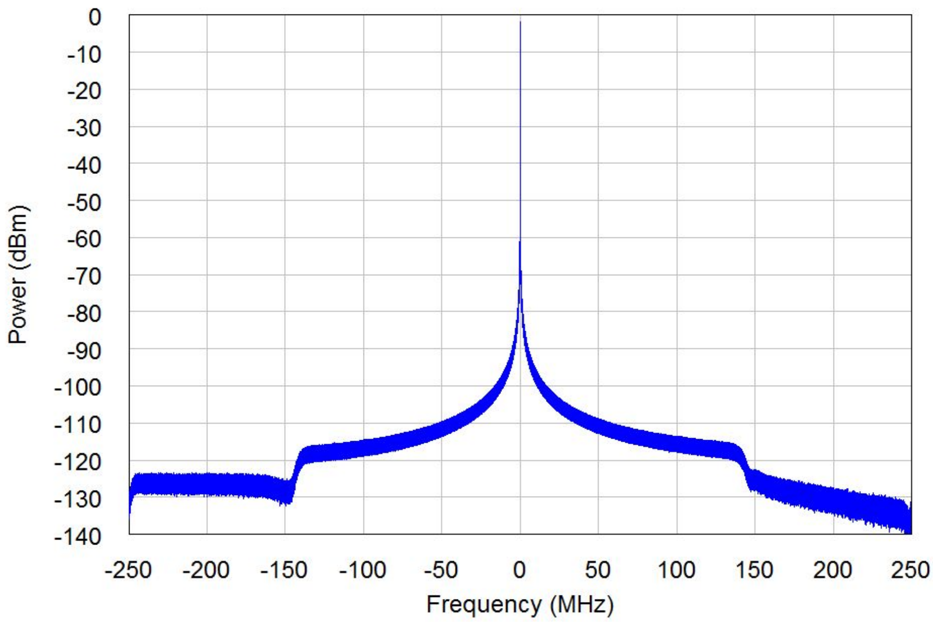
The amplification of this signal needs to be done in order to achieve a more suitable power level for the signal to be analysed and overcome the threshold of detection. The parameters that could modify this amplification are the ones named in the transmitter block : IP3, P1dB or NF.

They can modify the spectrum of receiver signal, however the power level will be lower than the one in the transmitter block so it may not reach the level of power where the gain starts to be affected by these parameters. We should test the power received and the attenuation introduced by antennas and hybrid in order to guess if the gain will be linear or not at this level of power.



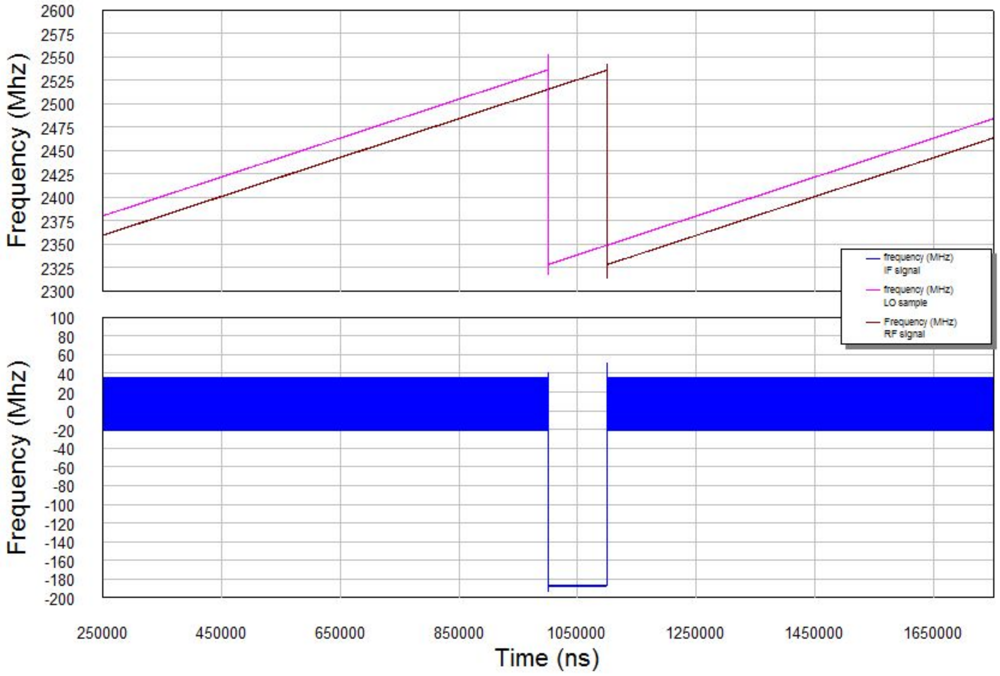
Graph 4.10.. Amplification of received signal

The next element that plays a part in the receiver system is the mixer. If both input signals, LO sample and RF signal are not delayed, the frequency obtained from the subtraction of frequencies is cero. In this case, we would obtain a pulse place in 0 Mhz which frequency will be the addition of the power in both signals in dB.



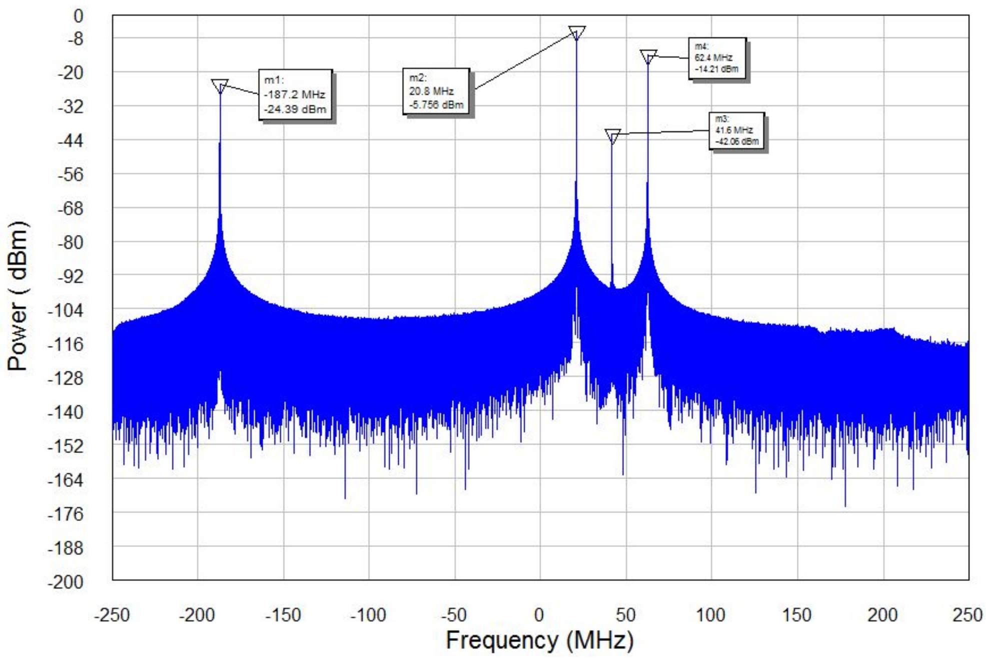
Graph 4.11. Power spectrum from IF port from mixer and 0ms delay.

In the real system, in the presence of a detected target, the transmitted pulse will be shifted due to the delay in reception of the echo. It is possible to see in Graph 4.12. , that for a delay equal to 0.1 ms the instant frequency is shifted when comparing it with the transmitted pulse.In the graph below, it is shown the frequency obtained at the out port of the mixer result of the sustraction to the frequency at its inputs.



Graph 4.12. Shifted pulse caused by detection of target

In this case, in the presence of a delay equal to 0,1 ms, more tones will appear in the spectrum of the detection like it happens in Graph 4.13. Tones in 183 Mhz and 20.8 Mhz are created by the difference between frequencies in pulse transmitted and received, whereas tones in 62.4Mhz and 41.6 Mhz are intermodulation products of the them.



Graph 4.13 . Power spectrum in presence of detected targets

2. Determination of radar parameters.

The best way of testing the system designed is creating a scenario where a target is detected and the antenna receives an echo reflected from it. To simulate this detection, it is going to be suppose the existence of a target, whose RCS is equal to 1 m2 and that is situated 1 metre distance from the detector.

For this simulation, the power received is going to be computed theoretically from the values extracted at the beginning of this chapter. The transmitted power is going to be considered as 18.82 dBm and the gain of the antenna array will be equal to 6.25 dB as calculated in the third chapter of this text.

Formula 4.1 extracted from [1], is going to determine the value of the received power for all quantities described in previous paragraphs.

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}. \tag{4.1}$$

The power received is equal to 5uW. Knowing this, in the simulator it is necessary to adapt losses and delay of the received signal to the ones that it would have in a real system. The antenna will be substituted by a block that will introduce and RF delay and some attenuation. The delay needed for a distance equal to 1 metre can be calculated by using Formula 4.2., whereas the attenuation can be extracted from the difference between transmitted and received signal.

$$delay = \frac{distance}{2\,c} \tag{4.2}$$

2.1. Noise at the receiver.

According to [1; pp.679-681], it is possible to calculate the level of noise in the system by calculating the noise temperature of each element on it.

The elements can be divided by the losses generated by passive elements such as filters or hybrid and elements that modify the received signal such as the mixer and amplifier.
All elements listed as passive before are designed by using coupled transmission lines, their losses are determined by the attenuation in the passband shown in parameters S12 in the case of the filter or parameters S24 and S34 in the case of the hybrid. Losses for both filters and hybrid will be established equal to 0.5dB. For this value of losses and using formula 4.3, the noise temperature obtained for each of this element is 36K.

$$T_{\mathrm{TL}} = (L_T - 1)T_p \tag{4.3}$$

where T_p: physical temperature; L_T :losses in the transmission line; T_{TL} : temperature at the antenna.

$$T_{\mathrm{REC}} = T_{\mathrm{RF}} + \frac{T_M}{G_{\mathrm{RF}}} + \frac{T_{\mathrm{IF}} L_M}{G_{\mathrm{RF}}} \tag{4.4}$$

where Trec : receiver temperature; T_M : temperature of the mixer; T_{RF} : temperature of the amplifier; G_{RF} : Gain of the amplifier; T_{IF} :temperature at the output of the receiver; LM: conversion losses at the mixer

Regarding the formula 4.4 and the values needed for the calculation, it is necessary to specify that the gain of the amplifier is 18.5 dB, the noise figure values of mixer and amplifier are 7.5dB and 4 dB respectively and the conversion loss at the amplifier is 10dB.
So, once computed all calculations, the receiver temperature T_{REC} obtained is 470 K.

The noise temperature for the antenna could be calculated by applying Formula 4.5 in which the radiation efficiency η_{rad} is equal to 0.8. The brightness temperature T_b and the physical temperature T_p are equal to 200K and 300K respectively.

$$T_A = \eta_{\mathrm{rad}} T_b + (1 - \eta_{\mathrm{rad}}) T_p. \tag{4.5}$$

$$N_i = kBT. \tag{4.6}$$

where N_i: noise level; k : $1.38 \cdot 10^{-23}$; T: temperature ; B: bandwidth of transmitter signal

For this values the noise temperature of the antenna, T_A, is equal to 219.3 K. So the noise value at the antenna,N_i , calculated using Formula 4.6 is equal to N_i = -122dB = 6.29e-13 W
The final calculation needed in order to obtain the value of the noise in the received system is the sum of all noise in all elements of the system. This will be made by using Formula 4.8 for the calculation of the noise temperature of the system.

$$T_{\mathrm{SYS}} = T_A + T_{\mathrm{TL}} + L_T T_{\mathrm{REC}} \tag{4.7}$$

The noise temperature of the total system is equal to 853,7K. Using Formula 4.6, we obtain a **noise level** , No, of **-116dB** or **$2{,}45 \cdot 10^{-12}$ W .**

All formula used for these calculations were extracted from [1; pp.679-681], so for further information about noise level and its computation, check this resource.

2.2. Range of radar

In order to characterize the radar, it is essential to determine its range. The range, as described in Chapter 2, is the maximum distance at which a target could be detected.

$$R_{\max} = \left[\frac{P_t G^2 \sigma \lambda^2}{(4\pi)^3 P_{\min}} \right]^{1/4} \tag{4.8}$$

In the previous paragraphs, it was established that the noise level at the antenna was equal to 6.29e-13 W, this level is defined as the minimum level of power needed in order to detect a target. Using formula 4.8., the maximum range obtained is 43.42m.

The bottom line here may be the limitation established by the low pass filter in the receiver. The bandwidth of this filter goes from 0 to 20 Khz, so all blanks detected should be placed within this band.
A target placed 43.42 metres away from the target would generate a blank in frequency equal to 60 Khz. The filtering would not allow the detection of this target due to the attenuation in he frequencies out of the bandpass of the filter.

For that reason, the maximum range will be determined by the bigger frequency of the passband of the filter, 20Khz.

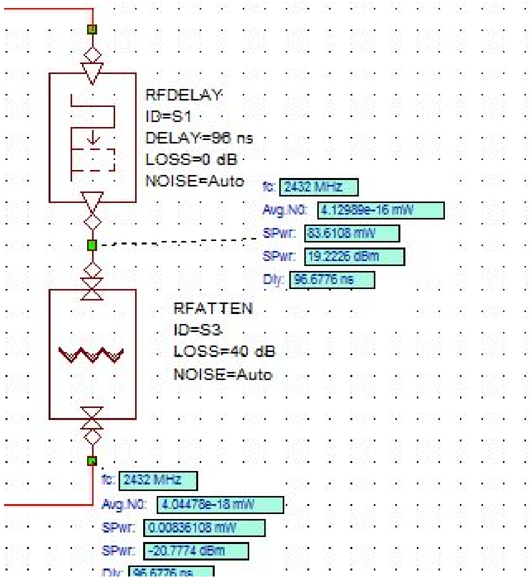
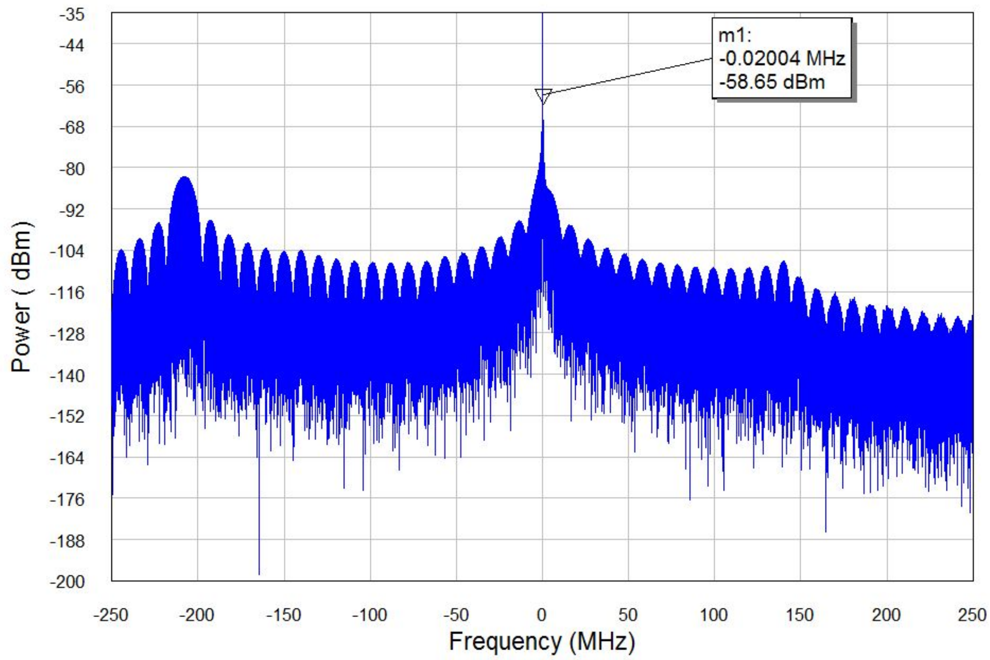
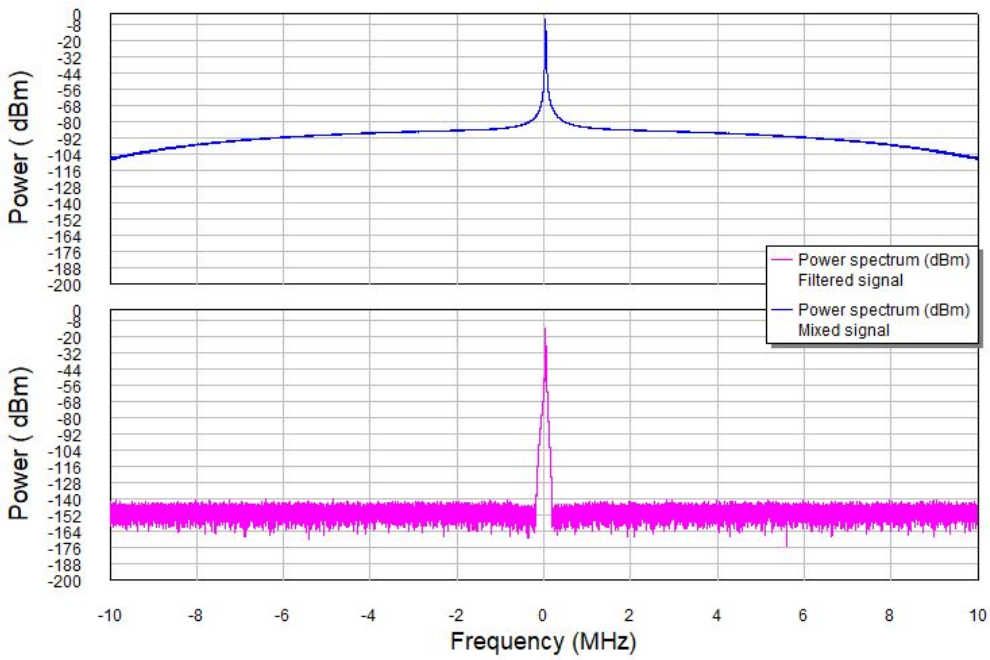


Figure 4.3. Delay and attenuation cause by detection of a target at Rmax



Graph 4.15. Detection of a target at Rmax distance

After filtering the signal it is possible to appreciate a single tone place in 20 Khz and a level of noise close to -140 dBm.



Graph 4.16. Detection of a target at Rmax distance. Filtered signal.

According to the calculations made by using Formula 4.9 and Graph 4.16, a target situated 14.44 m away from the detector will place a blank in 20Khz frequency and a delay in the received pulse of 96ns.

The **maximum range** for the radar will be equal to **14.44m.**

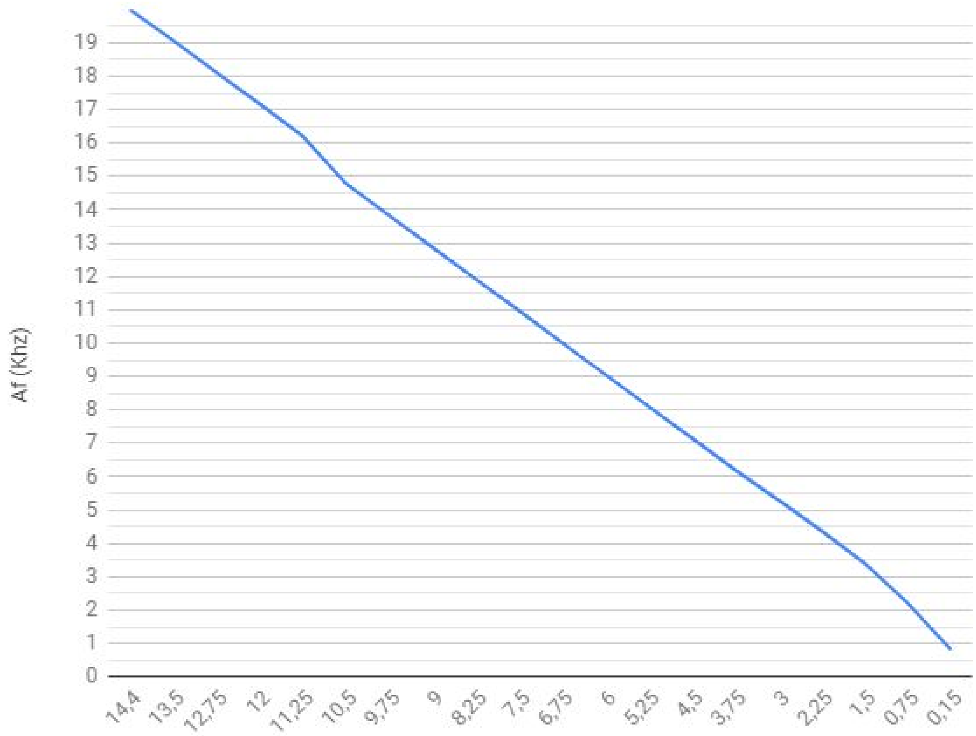
2.3. Frequency of target detection.

For the detection of a target, however, the only information available will be the power spectrum of the signal at the output of the low-pass filter like the one shown in Graph 4.16
In Chart 4.1 , it is possible to see a relation between the delay of the received pulse, the distance to the target and the position and power of the blank detected.

Delay (ns)	Distance to the target (meters)	Blank position (Khz)	Power received (uW)	Power received (dBW)
96,15	**14,442**	**20**	0,01109175377	-79,5499978
90	13,5	**19,07**	0,01435869975	-78,42884886
85	12,75	**18,12**	0,01804718413	-77,43590551
80	12	**17,17**	0,02299986062	-76,38274796
75	11,25	**16,21**	0,02977419981	-75,26159901
70	10,5	**14,78**	0,03923674681	-74,06307008
65	9,75	**13,83**	0,05277542332	-72,77568274
60	9	**12,87**	0,07269091751	-71,38519849
55	8,25	**11,92**	0,1029519067	-69,87365606
50	7,5	**10,97**	0,1507318865	-68,21794865
45	6,75	**10,01**	0,2297391961	-66,38764903
40	6	**9,06**	0,3679977699	-64,34154813
35	5,25	**8,1**	0,6277879489	-62,02187025
30	4,5	**7,153**	1,16305468	-59,34399867
25	3,75	**6,2**	2,411710185	-56,17674883
20	3	**5,3**	5,887964318	-52,30034831
15	2,25	**4,37**	18,60887488	-47,30279884
10	1,5	**3,4**	94,20742909	-40,25914848
5	0,75	**2,21**	1507,318865	-28,21794865
1	0,15	**0,8**	942074,2909	-0,259148479

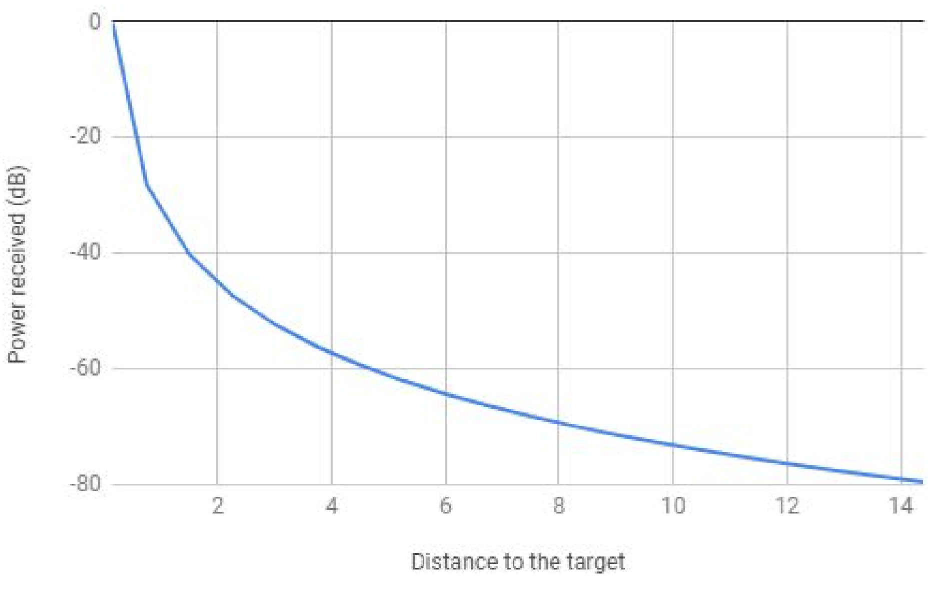
Chart 4.1. Frequency, power, delay and distance of a target within the Rmax level.

In Graph 4.17, it is shown the evolution of the target's position in frequency along with the distance to the target. A target placed 3 metres away from the radar will generate a blank at 5.3 Khz, whereas a target placed 10 metres will generate a blank at 14.78 Khz. All values shown in this chart were computer using AWR simulation of the radar system. The nonlinearities of the components in the system can be identified as the non linearities in the graph.



Graph 4.17.Evolution of blanks frequency along with distance.

The power received decreases with the increase of the distance to the target as it is shown in Graph 4.18. A target placed 5 metres away from the detector will generate an echo with power equal to -50 dBW, whereas a target placed 1 metro away will generate an echo equal to 0.2 dBW



Graph 4.18. .Evolution of blanks power received along with distance

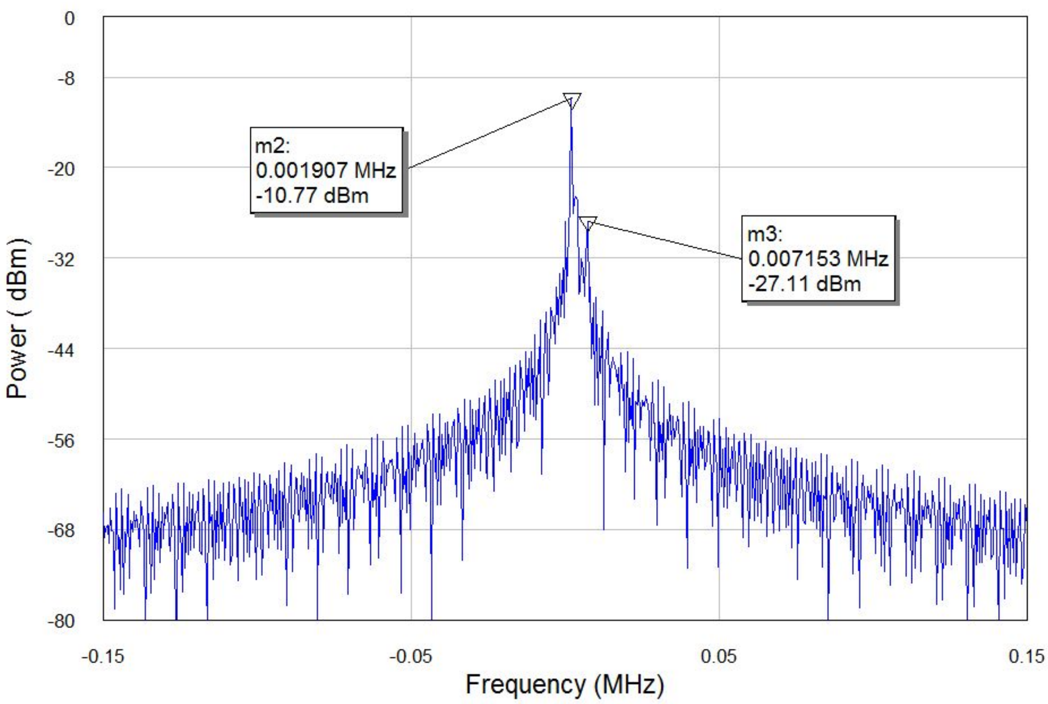
2.4. Resolution of radar

The resolution of radar is its ability to detect two targets in a short distance. It is determined by the bandwidth of the transmitted signal.

$$Sr \geq \frac{C_0}{2\,BW} \tag{4.9}$$

In this system, the bandwidth ot the signal is equal to 208 Mhz, so applying Formula 4.9 the value of the **radar resolution** is **0.7211 meters**. This quantity means that two targets separated a distance lower than 0.7211 metres will interfere with each other and it will not be possible to determine the position of the two targets with exactitude.

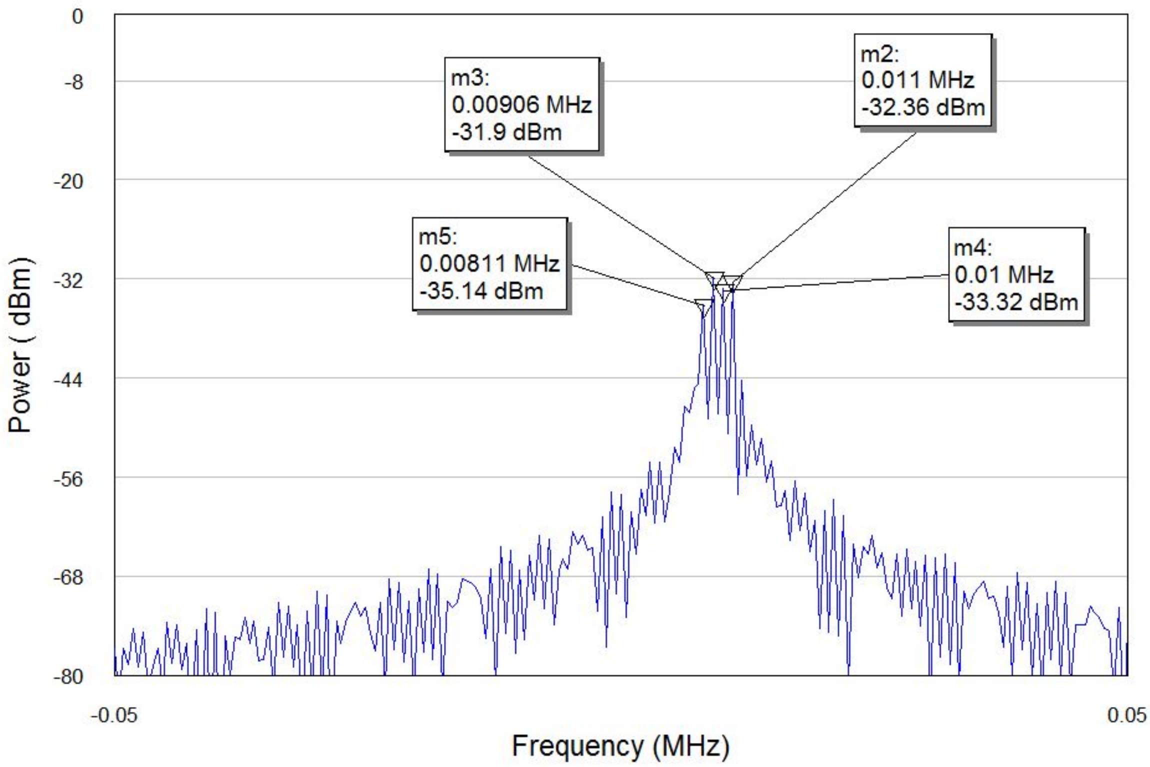
As an example we can consider a pulse delayed 90 ns and another pulse delayed 30 ns. This means a difference in distance of 9 metres between targets. In Graph 4.19 are shown the blanks that are going to be found in the spectrum.



Graph 4.19 Detection of two distanced targets.

Considering the results observed in Graph 4.19, it shows two different targets with different level of power that could be easily identified. With the values shown in the graph it will be possible to determine its position in space with accuracy.

As a different example, we can consider a pulse delayed 40 ns and another pulse delayed 45 ns. This means a difference in distance of 0.7 metres between targets. In Figure 4.20 are shown the blanks that are going to be found in the spectrum.



Graph 4.20. Detection of two close targets.

It is possible to see some interferences and intermodulation products created by the tones of the targets detected due to their closeness. This intermodulation products are created by the amplifier and the mixer of the receiver block and their parameters IP3 and IP2.

The blanks placed at frequencies 10.01 Khz and 9.08 Khz correspond to the targets detected. The blanks situated at frequencies 8.1 and 11Khz are generated by intermodulation products in of frequencies mentioned before.

$$|2 \cdot f1 - f2| = |2 \cdot 9.08 - 10.02| = 8.12 \text{ Khz}$$
$$|2 \cdot f2 - f1| = |2 \cdot 10.02 - 9.08| = 10.96 \text{ Khz}$$

This two peaks in power could create the fantasy of two different targets place there. For that reason, the radar detection gets compromised when the difference between pulse is lower than 0.72 m.

Chapter 5

Conclusions

At the beginning of this project, we enumerated the objectives of this project along with the problems we expected to find in order to achieve them. As a conclusion, we will explain the solutions given to these problems during the design and development of the radar system.

Some of the solutions given have been implemented in the prototype of the radar constructed, some others won't be implemented due to the lack of proper materials, technology or knowledge needed.

However, all of them will be explained and specified in following charts in order to show for each objective enumerated in the first chapter, the problems found to achieve it and the solution to each one of them.

1. Achieved objectives.

The main objective of this project was to cover the basic principles of radar system and its design. We also aimed to gain knowledge regarding important aspects of the design of this system. Some of the aspects mentioned at the beginning of this text were circuit theory, radio frequency regulations and signal, signal processing, electromagnetics and some others.
The design, test and construction of the synthetic aperture radar gave us the opportunity to dig deeper into each of the aspects mentioned before.

Each component that takes part in the proper functioning of the radar system was studied, analysed and designed regarding some aspects related to circuit theory and RF signals. One of these aspects was the creation and preservation of the RF signal along all the radar process. This process includes the chirp signal that performs the modulation inside the pulses and the echo receive from the reached target.

The antennas in the charge of the transmission and reception of the waves and echoes were designed and required for that matter knowledge related to radio frequency legal regulations, electromagnetics and radio frequency. And thanks to the knowledge gained during this project, they were design and optimised for the correct transmission in our band.

Thanks also to the knowledge gained regarding signal processing during this bachelor, it was possible to understand the process.

Regarding the proper functioning of radar, there are some aspects of its design that were need to be taken in count.

For determination of a suitable reach for the radar, the parameter that has the strong influence in the maximum range of the radar is PRT, that has been set to a suitable value of 1ms in order to have a long pulse with high energy but whose length value would assure a range value big enough for detection of targets.

The detection of targets is directly related to the amount of power transmitted, that in this case was close to 18.8 dBm. The signal was amplified by 18.5 dB and all losses in filters, couplers and splitters were set to the minimum in order to preserve the power in the bandwidth of transmission. The directivity of the antenna and the array disposition increased the amount of power transmitted along with the possibility of reaching a target.

The noise in the receiver was minimise by including a 3dB hybrid coupler that prevents the coupling from the high power levels of the transmitted to the sensitive components of the receiver. The low levels of attenuation imposed to the filters design also helped to decrease the noise level at the receiver.

Another objective of this radar design was to minimise the interference of the transmitted signal with the non-free band of the spectrum. This goal was achieved by adding filters that preserve the established bandwidth and by minimising the effect of intermodulation products and DC voltages that could alter the frequency of the signal.

2. Solutions not implemented.

Regarding the aspects mentioned in the previous lines, there are some solutions or improvements that weren't implemented in the design or that were discard due to the lack of proper tools, components or budget.

It is true that when creating the modulatory signal, in this case a chirp signal, that will be transmitted, the amplifier chosen should be one with maximum gain that can ensure that the power of the RF signal is big enough for transmission. Regarding the receiver block, the objective is to reduce the noise in the received signal. For that reason, it will be required for the amplifier to reduce noise in the system rather than increase the power level of the signal.

However, in this study, the level of abstraction was kept in system design rather than component. For this reason, the components with the most suitable properties were bought and not design and constructed. An interesting study would be to create an amplifier with better performance regarding this matter.

Another important aspect to be implemented could be the addition of an IQ modulator that would allow us to determine the Doppler´s frequency. The velocity of the target could be estimated by the changes in distance along time, but the modulator will perform a more precise prediction of the real velocity of the target.

The antenna design could also be improved to increase its directivity and gain. This improvement will increase the power that reaches the target and assure that the received echo will have appropriate level of power.

Another way of improving this system that has been not yet implemented could be the use of an algorithm that can sum up the echoes obtained in the transmission of several pulses. It would guarantee better resolution to the image obtained.

The main and most important aspect not implemented was the construction of this system that would allow us to test the behaviour of each component and the radar itself. It would have been necessary to test the accuracy of all parameters given by manufacturer along with all parameters determined for the radar system such as range, noise or resolution.
External problems, completely out of our hands, didn't allow us to implemented it. For that reason, this part of the project is left for future studies.

Chapter 6

Legal regulations regarding this study

After all calculations and simulations, it is necessary to specify and explain all the legal regulations, laws and rules that were taken in count during the design and construction of this system.

Most of the laws taken in count are related with the spectrum of radio frequencies and the bandwidth of the signal radiated from the antenna.

1. Regulation for use of the spectrum

For the regulation of the spectrum, each country has its own institution that defines the band of frequencies for each application or service.
The regulations define also the free band of the spectrum that will be available for radio amateurs or some other services that don't have any reserved or private band.

In Spain, these bands are defined by the General Law of Telecommunications that includes the National Table for Frequency Allocations.

There are also some international institutions that regulates the use and division of the spectrum.

1.1. Institutions that regulate the use of spectrum

1.1.1. General law for Telecommunications. [3]

The general law for Telecommunications was last updated in 2017 and it regulates all telecommunication services, the radio frequency spectrum and some other aspects related with it.
For the system design, the most important chapter of this law is Title no. 5 that defines the regulation and use of the spectrum.

1.1.2. National Table of Frequency Allocations (CNAF). [4]

The national table of frequency allocations is included in the General law for Telecommunications. It defines the band of frequencies reserved for each use or application along with the band meant for free use.

1.1.3. International Telecommunication Union (ITU) [14].

International institutions also have some influence in the regulation and division of the radiofrequency spectrum.
The international Telecommunication Union is an agency for United Nations that regulates all issues regarding information and communication technology.
Its most important task is to regulate de radio spectrum, improve telecommunications infrastructure, satellite communications and some other issues regarding communications.

1.2. Application to the project design.

Regarding this project, we considered the limitations established by the General Law for Telecommunications [3] in his National Table for Frequency allocations[4] for the free band of the spectrum. It publishes a chart where it divides the spectrum for each of the uses allowed by the General law for Telecommunications.

According to their specifications, the free band of the spectrum that allow us to transmit in a band close to the one defined by our system goes from 2.093 Ghz to 2.9 Ghz.
The bandwidth of propagation for our signal goes from 2.324 Ghz to 2.536 Ghz, it respects the advices of these institution for the use of spectrum without license.
Two passband filters, one at the emitter side and one at the receiver will assure that the signal won't overcome this frequencies and they will prevent distortion in some other frequencies in the spectrum and the other way around.

There are also some limitations regarding power of the radiated wave. The rules applied for the radar system are the same that would apply to OFDM modulation. The maximum equivalent isotropic radiated power (EIRP) is 20 dBm.
The power of the generated signal is 18dBm that would be a value below this level, however the antenna gain that should be summed to this power in order to compute the EIRP, so the final value would be 24,6 dBm.
The values provided by the manufacturer, such as the gain of the amplifier, usually differ from the ones obtained at the laboratory. However, if the power obtained in the laboratory overcome the level established, it will be possible to use an attenuation with 5 dB of attenuation.

Chapter 7

Economical and social aspects regarding this study

In the following chapter, we will describe the social impact of this project in the students community and in future bachelor thesis that could be related with this matter.

We will also compute the contribution of each element to the budget of this project. For this budget, laboratory tools and programs licenses will be taken in count along with daily work and contribution of tutor and student.

1. Social aspects regarding this study

1.1. Impact in a Technology Telecommunications bachelor.

In order to mention or explain the impact of this study in a Telecommunication technology bachelor, it is important to take into consideration all technical aspects and knowledge applied and acquired during the design and development of the radar system.
We applied knowledge from microwave systems and RF signal, that was the basis for the description of the generation of chirp signal or the changes on the received signal. It is also important to understand how to process signals or results in order to obtain the maximum information from the target reached.
All the aspects mentioned before such as circuit theory, RF, signal processing or analysis of results perfectly sum up all topics studied in a Technology Telecommunications bachelor. For that reason, we could say that the construction of a radar system is a perfect way to test all knowledge acquire during these 4 years of studies.
As a suggestion, we may also say that the design of this system could be useful not only as a bachelor thesis but also as a course that could be include in the programme of Technology Telecommunications bachelor.

Some other things we need to mention while analysing the impact of this study are the future applications of all the conclusions extracted from this research.
Radar system can be analyse from different angles and each of them can provide a lot of studies and analysis. In this study, we intend to design the radar system, however, some other bachelor thesis in the future may be focus on the construction of the system, the design of one of its component, the improvement of detection, the analysis of the targets detected, possible applications of the radar system or even the statistic results extracted from the detection of targets and the estimation of their shape, distance, velocity or position. All of these studies would be extremely good candidates for bachelor thesis.

This text will be published in the open database of the university. All students will be able to access to it for consultation in the website of the university's library. Since it will be available for all student, it will possible to consult this resource to take it as a model for future bachelor thesis and also for doubts or consultations regarding subjects or courses.

2. Economical resources and budget for this project

2.1. Timeline of the project

In the following graph, it is shown the evolution of each task in the project along the months of this academic year.

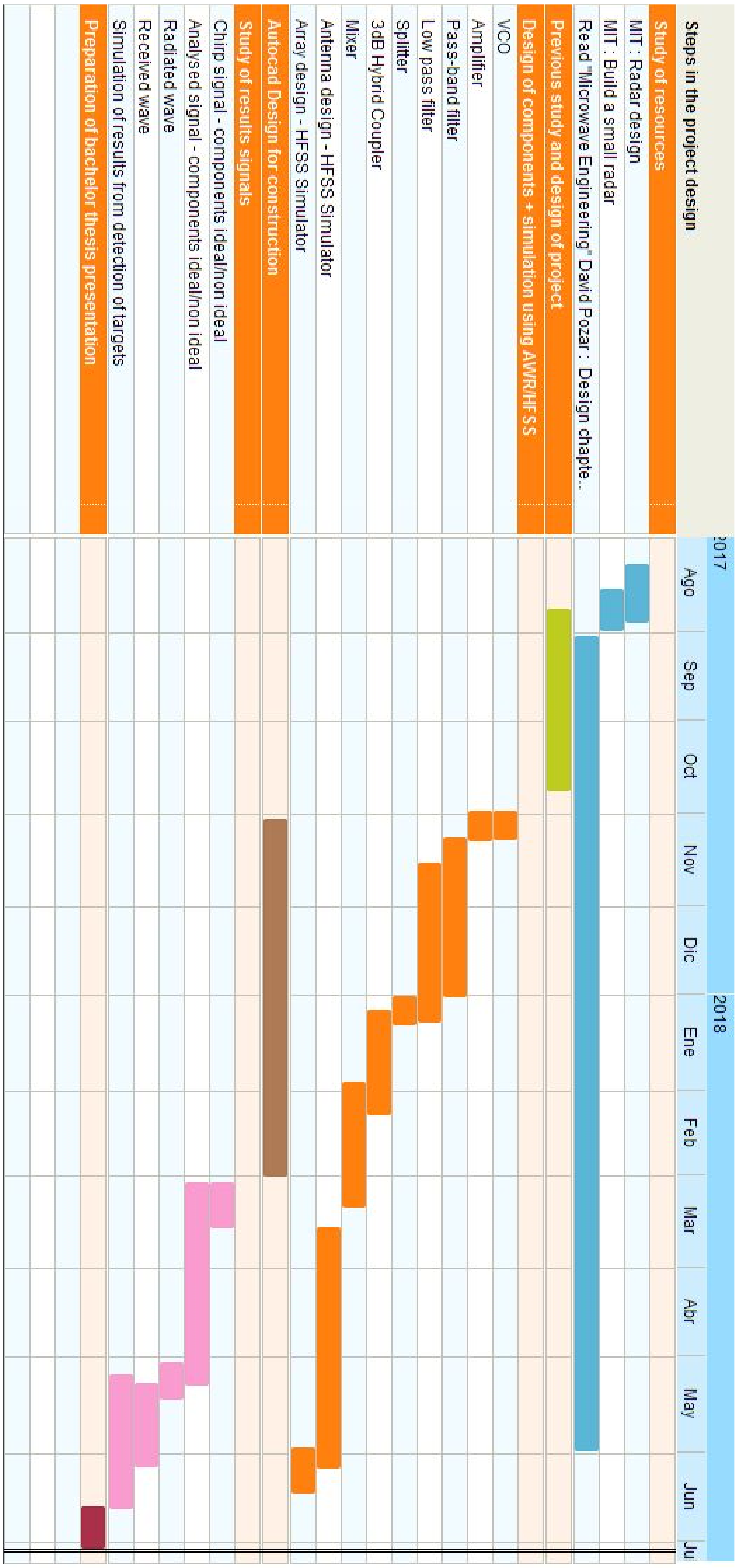


Figure 7.1. Timeline of the project.

2.2. Analysis of budget of the project.

For the budget of the project there are mainly two things that are need to be taken in count. The first on of them is the personnel budget, define as the human resources applied to this project; the other important contribution to this project budget is the amortisation cost, understood as all materials, tools and programs used for the performance of this bachelor thesis project.

1-. Description of the project	
Title	Design, test and construction of a small radar.
Author	Susana Maria Urdiales Monje
Department	Signal theory and communications (EPS - Carlos III University of Madrid)
Duration (months)	11
Indirect cost	20% (transport and others)

2-. Budget of the project (Direct cost)

PERSONNEL				
Surname, name	**Prof. position**	**Dedication (man month)**	**Cost man month (€)**	**Final cost (€)**
Urdiales Monje, Susana M	Engineer	7,5	2826	19782
Llorente Romano, Sergio	Senior engineer	0,3	4239	1271,7
			Total	**21053,7**

** Considering that man month quantity is equal to 141.3 hours. Maximum 12 man month : 1695.6. hours
Guessing an hourly rate of 20€/day for an engineer and 30€ day for a senior engineer.

EQUIPMENT, LICENSE AND LABORATORY.					
Description	**Cost (€)**	**% Usage in the project**	**Dedication (months)**	**Depreciation period (months)**	**Final cost ** (€)**
Daily work computer	800	80%	11	60	117,36
Computer at university laboratory	600	30 %	2	60	6
Microwave Office (AWR) License	15000	100%	11	60	2750
CST Studio Suite License*	2500	20%	3	60	25
HFSS Studio License*	3000	20%	2	60	20
Autocad License	2075, 15	80%	8	60	221,35
Matlab License	800	10%	2	60	2,6
				Total	**3142,31**

*Applying university license discounts.

***Considering that amortisation formula is calculated like*

$$(M / D) \cdot U \cdot C$$

M : Number of months the equipment has been used
D : Depreciation time - established in 60 months.
U : % of usage in the project duration.
C : Cost of the equipment.

3-. Final calculations for the budget.

BUDGET FOR FINAL COST OF THE PROJECT	
Description	**Contribution to final budget (€)**
Personnel cost	21053,7
Subcontracted tasks	0
Equipment, licenses and laboratories - Amortisation cost	3142,31
Other cost	0
Indirect cost (20%)	4839
TOTAL	**29035,01 €**

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